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Maximum Utilization of Water Resources in a Planned Community

Bacterial Characteristics of Stormwaters in Developing Rural Areas

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MAXIMUM UTILIZATION OF WATER RESOURCES IN A PLANNED COMMUNITY

Bacterial Characteristics of Stormwaters In Developing Rural Areas

by

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment for public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communications link between the researcher and the user community.

This project focuses on methods of maximizing the use of water resources in a planned urban environment, while minimizing their degradation. Particular attention is being directed towards determining the biological, chemical, hydrological and physical characteristics of stormwater runoff and its corresponding role in the urban water cycle.

Francis T. Mayo
Director
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PREFACE

The overall goal of this research was to evaluate the water resource plan for The Woodlands, Texas, and to make recommendations, as necessary, to maximize its effective utilization through alterations in design and management. Any recommended alterations were to be critically evaluated as to their compatibility with the natural environment.

Collection and utilization of stormwater runoff for recreational and aesthetic purposes was a major feature of the water resources plan at The Woodlands. Control of downstream flooding was also of great importance and so storage reservoirs, in the form of recreational lakes and wet weather ponds, were created by the developers. Water quality was a concern if the impoundments were to be aesthetically appealing and/or suitable for recreation. Therefore, a major sampling and analytical program was designed to monitor water quality and quantity at different locations in the developing area. The Storm Water Management Model (SWMM) provided the focal point for combining the water quality and quantity data into a predictive tool for design and management purposes.

SWMM was originally developed for highly urbanized areas and, therefore, was calibrated for this project in an urban watershed (Hunting Bayou). Subsequently, SWMM was modified to model runoff and water quality from natural drainage areas, such as The Woodlands. Because of the lag in the construction schedule at The Woodlands, the dense urban areas were not completed during the project period. Consequently, Hunting Bayou and other urban watersheds were sampled to provide a basis for predicting pollutant loads at The Woodlands in the fully developed state.

Water analyses included many traditional physical, chemical and biological parameters used in water quality surveys. Pathogenic bacteria were also enumerated since the role of traditional bacterial indicators in stormwater were conducted to assess the eutrophication potential that would exist in the stormwater impoundments. The source, transport and fate of chlorinated hydrocarbons in stormwater runoff was also investigated.

Several of the large Woodlands impoundments will receive reclaimed wastewater as the major input during dry weather. Besides their use as a source of irrigation water, the lakes will be used for non-contact recreation--primarily fishing and boating. Because the reclaimed wastewater must be disinfected, there was a concern about disinfectant toxicity to the aquatic life in the lakes. Consequently, comparative fish toxicity tests were conducted with ozone and chlorine, the two alternatives available at the water reclamation plant.

Porous pavement was considered by the developers as a method for reducing excessive runoff due to urbanization and an experimental parking lot was constructed. Hydraulic data was collected and used to develop a model compatible with SWMM, to predict the effects of using porous pavement in development. Water quality changes due to infiltration through the paving were also determined.

Bacteriological content of low flow and storm water runoff was determined for the purpose of comparing densities of indicator bacteria with densities of bacterial pathogens. Those, in turn, were compared with data developed from secondary treated chlorinated and unchlorinated municipal wastewater. This approach related the hygienic quality of the water when compared to new bacteriological water quality standards for contact and non-contact recreation purposes.

Hopefully, the results of this project will contribute in a positive way to the development of techniques to utilize our urban water resources in a manner more compatible with our cherished natural environment.

ABSTRACT

An investigation of low flow and storm water runoff bacteria content from rural and urban areas was conducted over a two and a half year period. Data were obtained for total coliform, fecal coliform, fecal streptococci, Salmonella sp., Pseudomonas sp., and Staphylococcus sp. for comparison to densities in known polluted sources such as secondary treated chlorinated municipal wastewater. The usefullness of the currently employed indicator groups of bacteria was evaluated with respect to the accompanying densities of pathogens. The hygienic quality of water when compared to new bacteriological water quality standards for contact and noncontact recreation was considered. Settling of stormwater suspended solids was closely associated with bacterial reductions in the water column. The most useful indicators of pathogen content in stormwater runoff were fecal coliforms. Total coliforms and fecal streptococci were poor indicators of pathogenic bacteria densities. Chlorine and ozone doses for disinfection of stormwater containing high (≃200 mg/l) suspended solids may exceed 8 mg/l and 32 mg/l, respectively. Regrowth of total coliforms occurs following disinfection. Indicator group densities in urban stormwater runoff can easily exceed rural runoff densities with continual increases occurring throughout a storm event. Fecal coliform densities exceeded 2,000/100ml in 13 of 24 monitored hydrographs and exceeded 200/100 ml in 22 of those hydrographs. Fecal coliforms and fecal streptococci yielded the highest correlations with the physical factors, flow, suspended solids, and turbidity.

This report was submitted in partial fulfillment of U.S. Environmental Protection Agency Grant No. R802433, by the University of Texas at Houston, School of Public Health under the (partial) sponsorship of the U.S. Environmental Protection Agency. This report covers a period from November, 1973 to June, 1976, and work was completed as of May, 1976.

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SECTION 1

INTRODUCTION

Meaningful decisions regarding effective management of water resources must be derived following the use and correct interpretation of water quality data. This is especially true of management of rainfall runoff, otherwise known as stormwater. An essential part of this investigation was to develop data which could be used for comparison purposes in assessing the quality of stormwaters. Of equal importance was the task of determining the effect of urbanization on stream water quality during storm events. The need for producing those results is emphasized by the meager amount of data existing today which are directed to the specific tasks stated above. Most of the emphasis on bacterial pollution has been placed in municipal waste water bacterial densities. Therefore it is justifiably important to compare municipal data with stormwater bacteriology from rural areas.

The Woodlands, Texas served as the principal test site for low flow and stormwater quality investigations, and is located approximately thirty miles north of Houston, Texas. A more detailed site description can be found in the water quality report to the U.S. Environmental Protection Agency by Rice University, Environmental Science and Engineering Department; Dr. W. G. Characklis, Principal Investigator (Grant No. R802433).

The uniqueness of the primary test site was its rural, forested, and semitropical setting. Pines and oak abound in the area with thick forest floor cover. The loblolly pine (Pinus taeda), shortleaf pine (Pinus echinata) and various oak species (Quercus spp.) constitute the majority of stands. The soils are of a red-yellow podzollic nature which are characteristic of a mild climate, abundant rainfall, and the mixed conifer-deciduous forest cover. While it is generally believed that soils of that type are highly leached, the test site forest floor always had a 0.5 to 4 inch leaf cover. Such decaying vegetation contributes considerable amounts of organic materials to the area and the underlying kaolinite clays which are found in those soils.

This test area has channel slopes of about 0.2% and land slopes of 0-2%, which yield low runoff coefficients (10-20% of reported precipitation values) (1).

In the earliest stage of this investigation (November, 1973) an intensive effort was made to determine the water quality of each of the principal streams in the primary test site. To that purpose field reconnaissance indicated that sixteen sampling locations would be required. Their locations are indicated in Figure 1 and described in Table 1. The majority of those locations were used for low-flow water quality sampling.

Storm event monitoring occurred principally at four locations: Stations P-10, P-30, the influent to Lake B (Swale No. 8), and the discharge point from Lake A. Station P-10 represented the stream water quality above development areas whereas P-30 waters indicated the changes with distance downstream with increased development.

The test site was well suited for testing insofar as the purpose of this investigation was concerned. Bear Branch, Panther Branch, and the two impoundments (Lakes A and B) were calculated to have drainage areas of the following areal magnitudes:

Location	Area Drained to that Point Acres (Hectares)
P-10	16,050 (6,497.9)
P-30	21,600 (8,744.9)
B-09	9,651 (3,907.3)
Lake B	337 (136)
Lake A	483 (195)

During periods of low flow, less than one cubic foot per second (<0.028 cu. m/sec) has been measured at Station P-04 and approximately 5 cfs (0.14 cu. m/sec) at P-30.

Lakes A and B were constructed to provide aesthetic value to the adjacent conference center and for the purpose of providing irrigation water for the golf course. Figure 2 represents their locations relative to Panther Branch sampling Station P-30 and shows the locations within the Lakes of sampling sites for the January 11, 1975 field survey. Locations which were chosen for bacteriological analyses of soils near the Lakes are also included in Figure 2. The following data characterize the lakes.

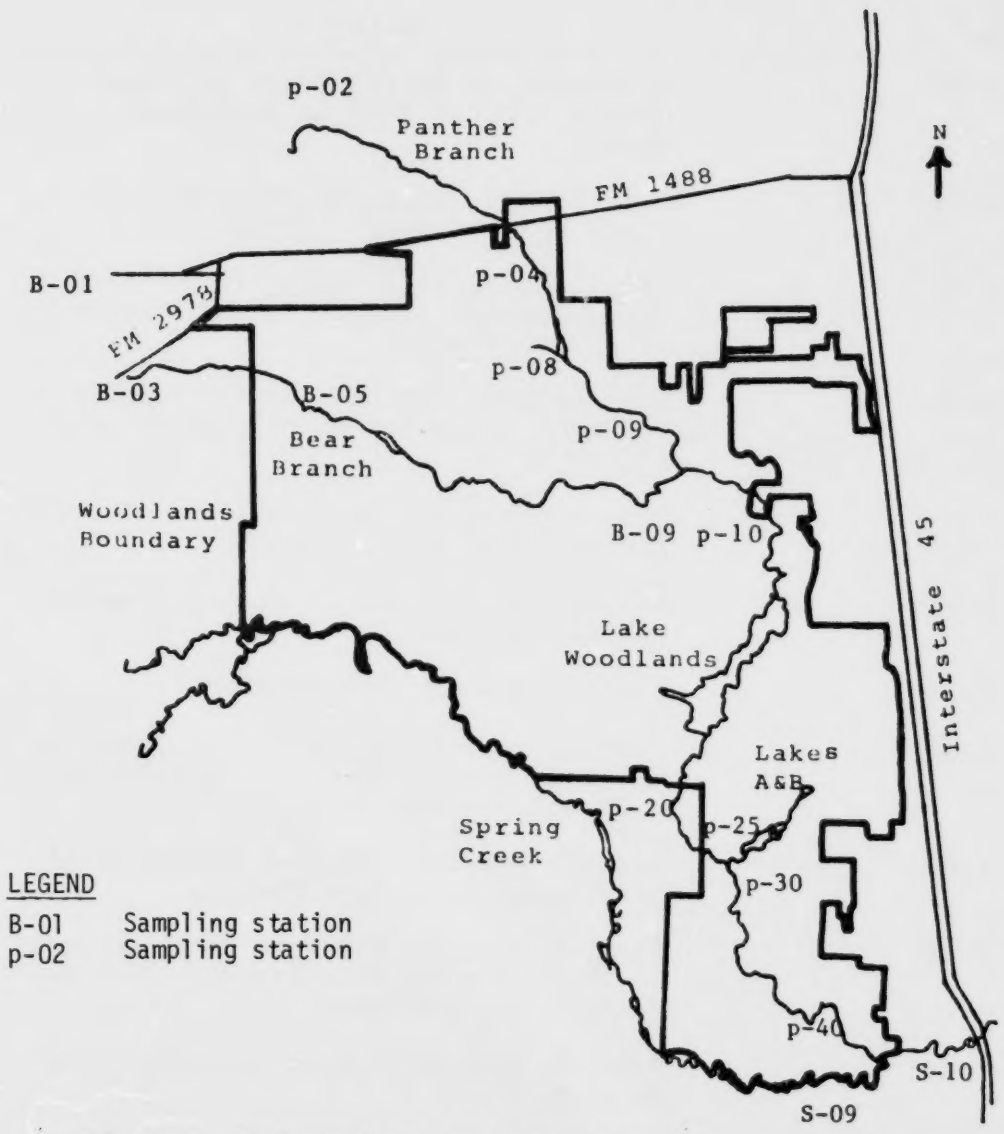


Figure 1. Principal surface waters in primary test site and original low sample station locations.

TABLE 1. DESCRIPTIONS OF LOW-FLOW WATER QUALITY STATIONS ESTABLISHED IN NOVEMBER 1973; THE WOODLANDS TEST SITE.

Station	Location
N-03	Southwest of Egypt, Texas on Egypt-Decker Prairie Road in Nickaburr Creek.
B-01	Bear Branch, vicinity FM 1488; 1.7 miles west of Egypt, Texas.
B-03	Bear Branch, in vicinity of FM 2978 (Egypt-Decker Prairie Road) southwest of Egypt, Texas.
B-05	Bear Branch, one mile below Station B-03; on Louis Lane, an unpaved road off FM 1488.
B-09	Bear Branch, 50 feet upstream of confluence with Panther Branch.
P-02	Panther Branch, NE of Egypt, Texas on Old Conroe-Magnolia Road.
P-04	Panther Branch, vicinity FM 1488.
P-08	Panther Branch, SE of Egypt, Texas on unmarked gravel road off FM 1488 in W.J. Jones State Forest.
P-09	Panther Branch, 100 feet upstream of confluence with Bear Branch.
P-10	Panther Branch, 500 feet downstream of confluence with Bear Branch. U.S.G.S. Station No. 08068400.
P-20	Panther Branch, 1 mile upstream from Station P-30.
P-25	Panther Branch, 1/4 mile upstream from Station P-30. North of Sawdust Road Gaging Station.

TABLE 1. (CONT'D.) DESCRIPTIONS OF LOW-FLOW WATER QUALITY STATIONS ESTABLISHED IN NOVEMBER 1973; THE WOODLANDS TEST SITE.

Station	Location
P-30	Panther Branch, U.S.G.S. Gaging Station at Sawdust Road. U.S.G.S. Station No. 08068450.
P-40	Panther Branch, 100 feet upstream of confluence with Spring Creek.
S-09	Spring Creek, 100 feet upstream of confluence with Panther Branch.
S-10	Spring Creek, vicinity Interstate Highway 45 at U.S.G.S. Gaging Station.

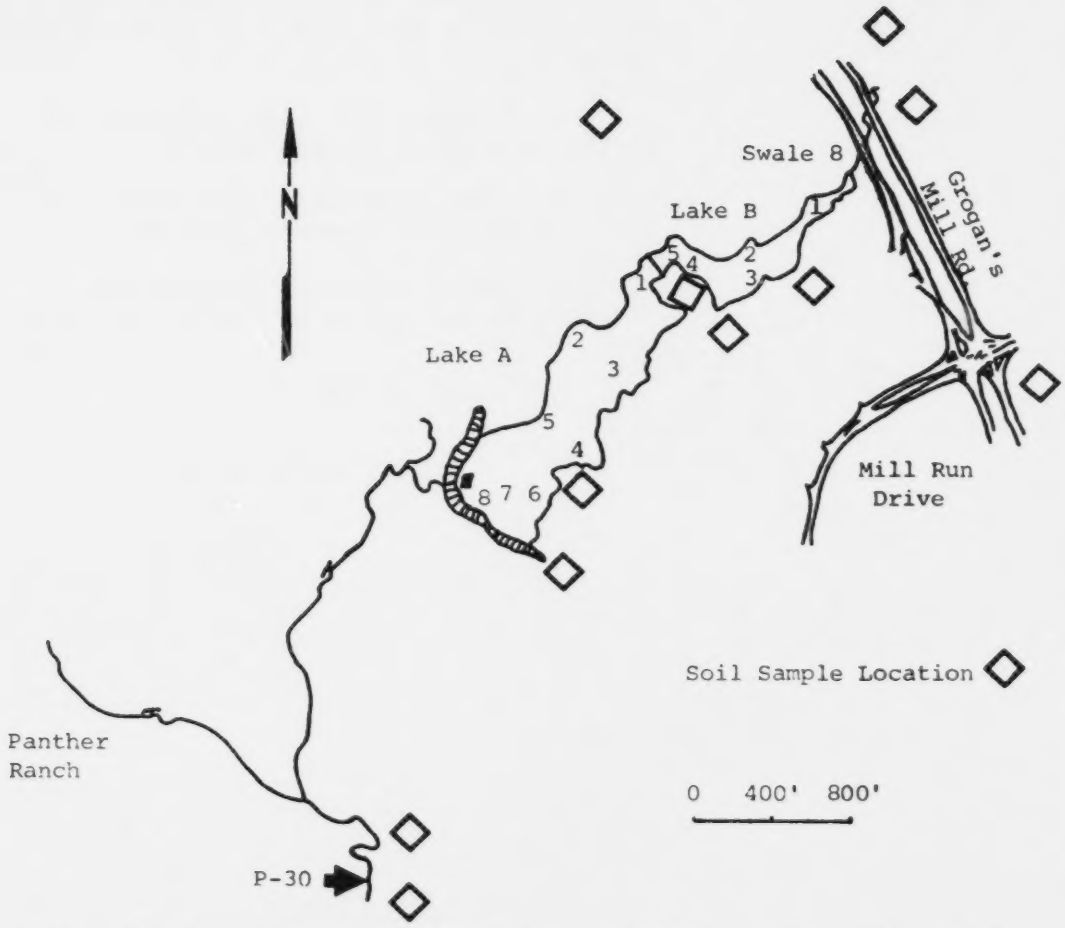


Figure 2. Locations of soil sampling sites and lakes A and B water quality sampling locations (1/11/75 survey).

Parameter	Lake B	Lake A
Length, ft. (m)	1,100(335)	1,400(427)
Width, ft. (m)	150-200(45.7-61)	300-500(91-152)
Depth, avg., ft. (m)	6(1.83)	8(2.44)
Surf. area, ac. (ha)	3.3(1.34)	12.6(5.10)
Volume, ac.ft. (cu.-m)	20(24,669)	90(111,014)

Two stream locations within the Houston metropolitan area were chosen to monitor storm events for the purposes of comparison of rural and urban storm runoff quality. The first of those two, Hunting Bayou, is located in northeast Houston and is designated as U.S.G.S. Station No. 08075760, Hunting Bayou at Falls Street, Houston, Texas. A flood-hydrograph partial record station is located in the drainage area of 3.50 square miles. Located in a heavily populated older neighborhood, the waters in Hunting Bayou at that location always showed signs of being heavily polluted with rubbish, free and floating oil, and other materials.

The other urban stormwater monitoring site was the Westbury site, located in southwest Houston in a drainage ditch at Atwell Street. The area drained is 210 acres (85 ha) and is composed of relatively newer homes, paved streets, and established lawns. Measurements were made at that location with a flow meter and staff gage.

OBJECTIVES

The period of time during which data were obtained from both field and laboratory analyses and measurements was from November, 1973 through May, 1976. That extent of time was divided into three units for reporting purposes: November 1, 1973 - May 31, 1974; June 1, 1974 - May 31, 1975; and June 1, 1975 - May 31, 1976.

The following eight objectives were to be accomplished during the project period: 1) monitor the bacteriological quality of Bear Branch and Panther Branch during periods of low flow as well as the low flow characteristics of Lakes A and B; 2) monitor the bacteriological quality of stormwater runoff within the primary test site (the Woodlands), including the stormwater inflow and discharges from Lakes A and B; 3) establish the relevance and usefulness of indicator organisms (bacteria) as indicators of the hygienic quality of stormwater runoff; 4) evaluate the aftergrowth potential of bacterial indicator organisms found in stormwater runoff; 5) evaluate the disinfection requirements of stormwater runoff; 6) compare the densities of indicator

bacteria in stormwater runoff with the densities of similar groups in municipal wastewater; 7) determine the changes imposed on stream bacteriological quality by urbanization of a rural forested area; and 8) to evaluate the effects of sedimentation on bacterial populations in stormwater runoff.

Those objectives included the enumeration of indicator groups and groups or genera of potentially pathogenic bacterial populations. The groups and genera which were identified, along with the codes used in this report are as follows: "TC" is total coliform; "FC" is fecal coliform; "FS" is fecal streptococci; "SS" are presumptive members of the Salmonella-Shigella group; "SA" is Salmonella sp.; "PS" is Pseudomonas aeruginosa; and "ST" is Staphylococcus aureus.

Other tasks were requested during the period of investigation due to questions concerning the sources of high bacterial counts and other related reasons. They consisted of the following: 1) assessment of the bacterial content of Hunting Bayou and the Westbury test site stream; 2) determination of the source of bacteria, i.e., stream sediment, soils, humus, or from swales; 3) determination of variability in blended sample counts; 4) determination of the variability in counts within a single sample, i.e. the precision and accuracy; 5) identification of count variability in a stream during low flow over a 24-hour period; and 6) determination of bacterial dieoff characteristics in refrigerated (4°±0.5°C) versus non-refrigerated (25°±1°C) samples for up to 24-hours.

BACKGROUND AND RELATED RESEARCH

The importance of accurate assessment of bacteriological water quality cannot be overemphasized. Elevated densities of pathogens have been directly implicated with onset of disease, and as far as that subject is concerned the literature is repleat with documentation of the public health importance of the indicator groups and pathogenic bacterial species. Several recommendations and sets of standards have been reported in recent years for bacterial quality of recreational waters. One report (2) suggested the addition of iodine and chlorine to a recreational lake for bacteria disinfection and algae control and recommended a level of fecal coliforms (FC) not to exceed 200/100 ml. Pathogenic content correlation with indicator bacteria is gaining more attention (3) due to the fact that all too often the total coliform (TC) counts do not represent the potential for infection. The American Chemical Society's official evaluation (4) of the TC test results was stated as follows: "There is no significant epidemiological basis

for the total coliform bacteria counts used today to establish standards for body-contact recreational waters."

Some numerical values for bacterial densities had to be chosen for comparison with those found during this investigation. The standards chosen were recently adopted by the Texas Water Quality Board (5). For contact recreation the fecal coliform geometric mean shall not exceed 200/100 ml with no fewer than 5 samples collected in 30 days and not more than 400/100 ml shall exist in more than 10% of the total samples in the 30-day period. For noncontact recreation the fecal coliform standard is one order of magnitude higher, i.e., 2,000/100 ml and 4,000/100 ml, respectively. Not only are standards being changed from TC, some authors recognize the need for specific pathogenic genera as water quality indicators. Pseudomonas aeruginosa and streptococci are among those which have received such attention (6,7). Pseudomonas aeruginosa is equally as important a pathogen as the Salmonella group. But testing for pathogens is far less amenable to routine analysis than TC, FC, and FS. The media available today are not as selective as they should be, especially for water bacteria. Most media developed for pathogen identification have been perfected employing clinical specimens. No doubt exists that pathogens may occur along with total coliform bacteria. Geldreich (8) reported that greater chances exist for Salmonella sp. isolation when fecal coliform concentrations exceed 200/100 ml. Attention is hereby directed to the data presented herein in which virtually all FC counts greatly exceeded that level. Geldreich further reported an 85.2% probability of SA isolation when the FC levels were 200 - 2,000/100 ml, and a 98.1% chance when they were greater than 2,000/100 ml. Bott (9) expressed the situation quite adequately in stating that due to the fact that many human pathogenic species are harbored in non-human hosts, it is generally unwise to limit one's concern to the subject of recent human fecal pollution as the sole source.

Earlier reports have avoided estimating the numbers of specific species which when ingested would result in the respective disease. Only recently, Rosenberg, of the Center for Disease Control, stated that it requires 10 organisms to result in shigellosis and between 10^5 and 10^8 for salmonellosis to occur (10). And waterborne disease incidences appear to be on the increase (10). A recent outbreak occurred at Crater Lake National Park (11) when 288 park employees and over 1,000 visitors were infected with the first reported toxigenic E. coli, serotype 06:H16. Application of the most bactericidal agent may not be the final answer in protecting the public health. Englebrecht

(12) reported an order of resistance to chlorine of the following organisms or groups: acid fast organisms > yeasts > polio type I virus > Salmonella typhimurium > E. coli. The implication being that other pathogens may survive chlorination attempts. With improved culture techniques, pathogens are finally receiving the attention they rightfully deserve. Highsmith and Abshire (13) found Pseudomonas to have occurred in creek waters in as large numbers as FC and in greater numbers than FS in all samples they tested. Pseudomonas sp., of course, can cause severe ear, eye, and nasopharyngeal infections. Furthermore, of all places to find large numbers of that pathogen, Carson, et al. (14) reported Pseudomonas sp. existence in hospital distilled water mist therapy units.

SECTION 2

CONCLUSIONS

A grab sample represents the stream condition only at one point in time. The diurnal coefficient of variability of indicators and pathogens in a small rural stream can be as much as 126% ($\sigma/\bar{X}$). Normal variability in indicator and pathogen growth using standard culture media for a single sample ranges from 9% for ST ($\sigma/\bar{X}$) to 35% for SA ($\sigma/\bar{X}$).

The indicator bacteria groups and pathogenic genera which were tested settled at different rates in quiescent stream water samples which contained suspended solids concentrations above 200 mg/l. ST settled effectively in 12 hours in secondary treated municipal wastewater but PS and SA populations tended to remain in suspension. TC, FC, and FS populations also did not settle effectively in the wastewater.

Blending of highly turbid samples up to 10 seconds can produce higher indicator bacteria counts. Additional blending time resulted in reduced counts probably due to cellular disruption by heat and shearing action. Some counts can be increased 56% but most groups increase to levels within single sample variability percentages. Blending is not feasible for storm water analysis due to time constraints in plating large numbers of samples and sterilization of blending equipment between samples.

Preservation of field samples for bacteriological analysis should be accompanied if the time between sampling and analysis exceeds 12 hours. Samples kept at 4°C and 20°C showed no significant differences in counts between TC, FC, FS, ST, and SA for up to 12 hours. However, PS increased in density in the refrigerated sample within 12 hours. In no cases were variances in samples greater than the diurnal field sampling variances quoted above.

Chlorinated secondary treated municipal wastewater exhibits FC/FS ratios ($\simeq$ 1.5) which suggest contamination of the water by non-human sources. Percent coefficient of variation variances in treated municipal wastewaters ($\sigma/\bar{X}$)

were significantly higher than in small urban stream over a 24-hour period and within settled versus agitated water samples containing high solids and turbidity.

Irrigated high humus soils can yield greater counts of TC, FC, FS, PS, ST, and SA than rural streams receiving no point source contributions. Stream sediment, surrounding soils, and impoundment sedimentary materials can contain greater densities of TC and ST on number/unit weight or volume basis than stream waters.

Under low flow conditions, small rural streams can exhibit differences in upper and lower reaches insofar as bacterial quality is concerned. On the average, station P-30, downstream, contained FC densities of 2.38 (log value) while the upper reaches had a value of 2.13. Compared to a contact recreation standard of 2.3 the lower reach was not acceptable for contact recreation. Statistically, this upstream log geometric mean was not different from the value for the waters downstream. But on the basis of the not to exceed 2.3/100 ml standard, the downstream waters exceeded the value. Bacterial concentrations under low flow conditions exceeded single sample variability and diurnal variability. TC were not reliable indicators of pathogen, FC, or FS densities under low flow conditions.

The impoundments investigated in the primary test site showed reduced FC, FS, and pathogen concentrations compared to inflow storm water concentrations. Dieoff and settling both contributed to reduced bacterial populations. TC concentrations, on the other hand, remained as high as in storm water, suggesting that that group of indicators may not be a reliable water quality index of pollution.

Excessive doses of chlorine or ozone are required for disinfection of storm waters which contain high suspended solids. Solids concentrations greater than 30 mg/l effectively reduce the disinfectant efficiency similarly. Impoundment waters during storm events exhibited a chlorine demand greater than 8 mg/l and an ozone demand greater than 32 mg/l. P-10 waters had a chlorine demand of 8 mg/l and P-30 waters had one of 8 mg/l to 16 mg/l, depending on the quality of the water. Given 2, 4, 8, and 16 mg/l chlorine doses, TC bacterial populations in storm waters behave similarly, i.e., decreases at thirty minutes followed by increases to 10^7/100 ml in eight days. FC, FS, and some pathogens decrease to 10/100 ml or lower and will remain at that level for up to eight days. ST can reestablish their populations after four days. All indicators and pathogens respond the same to ozone as to chlorine.

Urban storm runoff contains bacteria concentrations which may be two orders of magnitude higher than those in a small rural stream. Extreme variability can occur between samples in urban areas. Also, indicators and pathogens can continue to increase in concentration throughout a storm event in urban runoff. TC ranges of 3.1×10^4/100 ml to 7×10^8/100 ml can be found in urban runoff. In a well defined storm event in a rural watershed, TC concentrations show less clearly defined pollutographs compared to FC and FS. The term "pollutograph" conforms with the terminology established by the U.S.E.P.A. in usage of the Storm Water Management Model. Indicators and pathogens peak prior to the hydrograph peak during the first flush phenomenon and closely correlate with solids and turbidity peaking times. FC/FS values show more constancy in lower reaches of a small rural stream than in its upper reaches. FC, FS, and ST can peak earlier in the lower watershed than in upper stream areas. Rainfall duration and intensity can exert an influence on physical stream factors. Solids peaks during storm events ranged from 0.3 cfs to 1,250 cfs, and turbidity ranged from 4 J.T.U. to 2,000 J.T.U. Log mean value ranges for all Woodlands storm events were TC, 4.20-7.76; FC, 0.85-3.63; FS, 2.19-5.12; PS, 0.47-4.66; ST, 1.50-4.42; and SA, 0.28-1.94.

In thirteen out of twenty-four monitored hydrographs, the mean FC values exceeded a non-contact recreation standard of 2,000/100 ml and 22 of the 24 exceeded the contact recreation standard of 200/100 ml. 22 of 123 data exceeded a 4,000/100 ml FC standard. The exceptions were the impoundment effluent data, signifying the usefulness of storage reservoirs in stormwater bacteria reductions. Non-linear relationships exist between bacterial populations and physical factors in storm waters. Log transformation of bacterial data is essential to effective interpretation of pollutographs. FC and FS yielded the highest correlations with physical factors (Q, SS, T) for predicting stormwater quality. FC can increase as the turbidity and solids while FS decrease. FS can increase as the discharge and FC. FS was found to have been the most useful quality predictor. Relationships of FC and FS with highest correlations were

$$\text{Log FC} = .719 \log \text{FS} - .002Q + .003T + .002SS + .612 \quad (R^2 = .77)$$

$$\text{Log FS} = .720 \log \text{FC} + .002Q + .151 \log \text{TC} + .001\,T - .001SS - .170 \quad (R^2 = .82)$$

Multiple regression analysis and other statistical analysis approaches showed FC/FS values to have virtually no correlation for storm water compared to low flow conditions when examined together or separately. P-30 storm events yielded

much higher correlations than the waters in the upper reaches (P-10). The most significant indicator was

$$\text{Log ST} = .000668T + .779 \text{ Log FS} + .000625SS - .489 \text{ Log FC} + .167 \text{ Log TC} + 1.051 \quad (R^2 = .79)$$

Combining data from four stations in a representative storm event in the Woodlands (3/12-14/75) with 97 data points, showed PS and ST to have had the highest correlations.

$$\text{Log PS} = .000862T + .665 \text{ Log TC} - .0233Q - 1.757 \quad (R^2 = 8.5)$$

$$\text{Log ST} = .259 \text{ Log TC} + .000612T + .968 \text{ Log PS} + .0278Q - .209 \text{ Log FC} - .589 \quad (R^2 = .90)$$

In virtually all of the statistical analyses involving correlations of FC/FS values with pathogen densities, the R^2 values were less than 0.20 and none were significant at the 0.5 significance level. SA were the most difficult bacteria to predict in storm waters. Pathogens can be present in surface waters when indicators are either not present or in such low numbers that detection methods did not record them. Considering all data, when Salmonella sp. were detected, 6 samples contained no FC, 7 samples contained no FS, 29 samples contained no PS, and 3 samples contained no ST. Salmonella sp. were not detected when TC were 4,500/100 ml.

A graphical analytical approach can be a most useful tool in water quality analysis. This application showed distinct increases in FC and FS with increased urbanization, considering 5 land use areas (Figure 16). FC and FS distributions were not constant for different land uses. Statistical analysis (LSD test) determined that no significant differences occurred in FC/FS values for the following water sources: storms at Lake B (FC/FS = .53); low flow, Lake A (.58); chlorinated wastewater (.73); low flow at P-10 (.92); storms at P-30 (.97); low flow at Lake B (.99); low flow at P-30 (1.26); storms at Westbury (1.47); low flow at all Woodlands stations (1.68); storms at P-10 (2.11); and raw sewage (2.42).

The two-factor analysis of variance may be the most applicable approach to comparing bacterial concentrations between upper stream reaches (P-10) and lower reaches (P-30). No significant differences in TC concentrations were found between the two locations. But, FC were 2.7 times as concentrated in storm waters at P-30 (downstream) than at P-10 (upstream): FS were 5.2 times as concentrated, PS were 5.7

times as concentrated, and ST were 5.0 times as concentrated.

No statistical differences were observed in FC and FS concentrations on a seasonal basis during low flow conditions at the Woodlands. ST concentrations showed less variation between seasons than did PS or SA. TC concentrations were significantly higher in summer than winter and spring (statistically equivalent), and in turn those were significantly higher than fall and winter (statistically equivalent).

SECTION 3

RECOMMENDATIONS

Future investigations on water resources for bacterial assessment and management of storm water runoff should establish base flow diurnal variability in indicator bacteria concentrations prior to evaluating storm events. Concurrent identification of point sources should be accomplished in order that accurate decisions can be made relative to the need for specific treatments of the resource. In essence, the variables which exist in each individual area will dictate the quality of surface water runoff and they must be dealt with only on a one time basis.

If disinfection of storm waters is a measure which is being considered for pollution control in a specific area, several factors must be taken into account prior to application. The disinfectant demand of the waters should be established or adequate disinfection cannot be accomplished. Following that, it is essential that the need for disinfection on an area by area basis be justified, taking into account whether the public health would be endangered if disinfection were not carried out. Cost effectiveness should be considered if stormwater containing not domestic wastewater is to be disinfected.

Fecal coliform/fecal streptococci ratios have been proposed as reliable indicators of the sources of bacterial pollution. That concept is applicable only if an FC/FS value is established at the source. In view of the marked differences in concentrations of indicator bacteria in any water source with time, a factor which should also be taken into account is land use. Indicator bacteria as well as pathogens may demonstrate trends between low flow conditions and during storm events which are peculiar to each area taken into consideration. Total coliform bacteria were not reliable in relating pathogen content of the water sources. The high correlations of fecal coliforms shown earlier, again strongly indicate that they are a primary indicator of fecal pollution. Additional analyses should also be conducted for pathogen groups such as Salmonella sp., Pseudomonas sp., and/or Staphylococcus sp.

Through the years, physical and chemical tests for determining water quality have been refined to the point where most are highly accurate and precise. The science of aquatic microbiological quality (and quantity) assessment has lagged far behind in technique refinement. Membrane filtration techniques have made an appreciable improvement in this area. Yet, when using that technique with storm waters, the high solids content impedes some bacterial enumeration efforts due to the inability of the membrane to filter adequate amounts of water for proper enumeration. Clearly, alternative methods must be developed yielding equal or greater reliability for bacterial indicator and pathogen quantification. Additionally, most of the commercially available culture media were developed from clinical settings. Water quality assessment requires the use of more selective and more rapid identification types of media.

Settling and dieoff patterns of bacteria in impoundments with relatively short detention times suggest that if disinfection is to be applied to a particular storm water source, if at all feasible, the equivalent of stilling basins should be employed. That will significantly reduce the amount of disinfectant required and, of course, it will reduce the cost.

The time between when a sample is taken and when aliquots are cultured for bacterial analysis should not exceed twelve hours if the storage temperature does not exceed 20°C. Increased times may result in significantly different counts than were originally present in the water. That, in turn, could lead to erroneous conclusions regarding the quality of the water under consideration.

Chlorine is significantly longer lived than ozone in storm waters containing elevated solids concentrations. If disinfection is considered that factor should be taken into account prior to application.

Examination of bacterial data for comparison with other water quality parameters for analysis or resource management purposes should not be accomplished using a simple arithmetic approach because non-linear relationships exist between variables. Bacterial data should be transformed to $\log_{10}$ basis.

SECTION 4

MATERIALS AND PROCEDURES

Field sampling was accomplished by personnel from The Environmental Science and Engineering Department, Rice University, Houston, Texas and the University of Texas at Houston, School of Public Health, Environmental Science Discipline.

BACTERIOLOGY

The methodology incorporated in the laboratory research associated with this project involved standard techniques for assaying defined groups of bacteria, genera or species. Detailed descriptions for routine proven methods such as autoclaving media and glassware and membrane filter counting procedures are given in Standard Methods (15) and will not be detailed herein.

Water samples taken during periods of low flow were iced-down immediately and maintained in that condition until analyses could be conducted on each sample. All low flow analyses were initiated well within three hours after the samples were gathered in the field. During storm events, sample batches of six-hour duration were returned to the laboratory, at which time the dilution, filtration, plating, and incubation processes were started immediately. Reported bacterial numbers (colonies developed on the respective media) are the result of replicate plating in all cases.

During the time period of November, 1973 through May, 1974, methods which were applied for routine analysis for total bacteria populations, total coliform (TC), fecal coliform (FC), and fecal streptococci (FS), were those described in Standard Methods (15). Total coliforms, fecal coliforms, and fecal streptococci were counted on membrane filters. FS were identified on M-enterococcus medium. The Salmonella-Shigella group was identified with the aid of Bismuth Sulfite Agar (16, 17, 18). Pseudomonas sp. were identified and quantified with Pseudomonas Agar F (Difco) (19). Pseudomonas Agar F was deleted soon after the earliest phases of this investigation and a new medium, m-PA agar, was uti-

lized (20). Pathogenic Staphylococci were identified with Mannitol Salt Agar (18) only in the early phases of the investigation.

Confirmation of colony taxonomy as appeared on selective media such as Bismuth Sulfite Agar was checked by using a relatively new biochemical analysis system (21). The "API 20 ENTERIC" was employed in this regard. Briefly this system exposes a test organism (colony) to twenty biochemical tests. Positive, negative, or other reactions are recorded after the appropriate procedure is applied for analysis. The results are coded and the test organism keyed-out by means of established diagnostic hardware which differentiates between the species of bacteria in the Enterobacteriaceae.

Following May, 1974, all data for Salmonella were developed using the following procedure. XLD Agar (Xylose Lysine Deoxycholate Agar) (BBL) plates were inoculated with a precise volume of test water which was allowed to evaporate to near dryness at room temperature (25 ± 1°C). Incubation at 37°C for 24 hours followed. Typical colonies were counted and recorded. All typical colonies were then transferred to TSI (Triple Sugar Iron Agar) (BBL) slants which were then incubated for 24 hours at 37°C and their reactions recorded. Slants yielding positive reactions were subjected to further confirmation by use of API test strips which employ twenty-one separate biochemical reactions (21). A description of reactions of Salmonella sp. on XLD Agar and TSI Agar can be found in Standard Methods (15). At least 10% of the colonies were picked for confirmation.

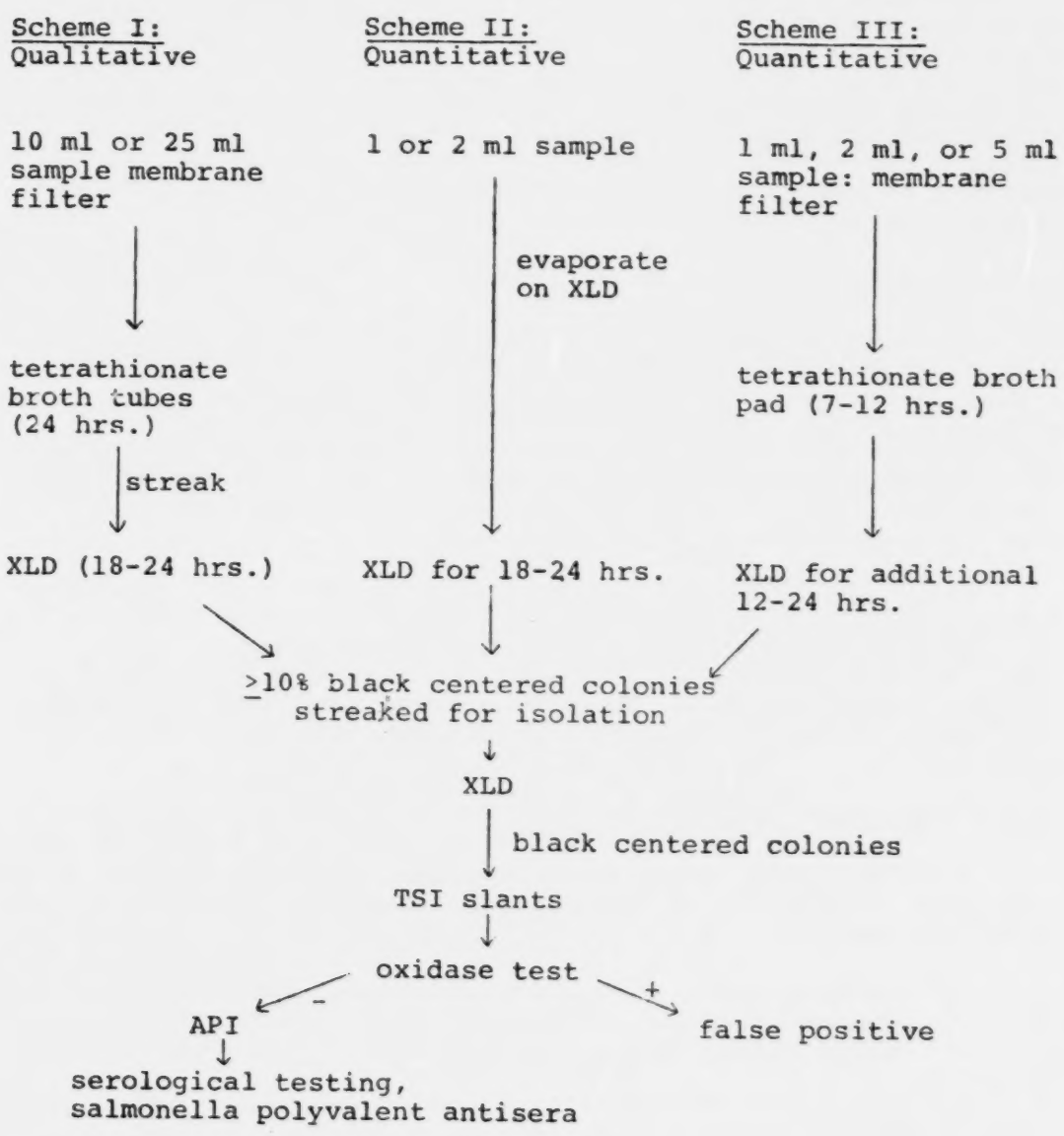
Vogel-Johnson Agar (BBL) was used for the identification of Staphylococcus sp. It isolates coagulase-positive, mannitol-positive staphylococci, Staphylococcus aureus, a proven pathogen, is easily isolated on this medium. It has been reported that Staphylococcus aureus is capable of isolation on that medium to the point of nearly excluding other forms (22, 23). Additional testing of Staphylococcus sp. was conducted using coagulase and catalase tests (22, 23). An example of the selectivity of the principal medium used for Staphylococcus sp. quantification lies in one series of picked colonies (60 total) of which 57 were coagulase-positive and catalase-positive, thereby confirming their identity. Attention is hereby directed to the pathogenic bacteria genus, Arizona. It was formerly named Salmonella sp. and is included in the numbers of Salmonella sp. reported herein. Citrobacter sp. was found to have been the principal false positive reaction organism on XLD plates but the total numbers found were less than 5% of the total positives.

As time progressed, the elevated numbers of Salmonella sp. which were being reported, especially from stormwaters in the Woodlands, began to be suspect. Further confirmation was accomplished using the schemes presented in Table 2. Schemes II and III were preferable due to the fact that quantification could be achieved by their use. Under crowded conditions many Salmonella colonies on XLD did not exhibit black centered colonies. Only well isolated colonies yield typical colonial morphology. On plates that are overcrowded, numerous black globs were sometimes observed but recovery efficiency of Salmonella sp. or Arizona sp. from those was low. These data are similar to those results presented by Kenner and Clark (24), conducted in U.S.E.P.A. laboratories. Their confirmation steps were not as extensive as those outlined above and followed throughout this investigation.

DISINFECTION EXPERIMENTATION

Methodology applied to water samples taken from the Woodlands sites for special studies of disinfection requirements during storm events and during periods of low-flow included the following procedures and equipment. Chlorine addition was accomplished by use of standardized solutions of sodium hypochlorite. Studies of break-point chlorination used the amperometric titration methods described in Standard Methods (15) for free available, total residual, and combined residual chlorine. Quantification of the amount of bromine added to water samples was accomplished by accurately weighing elemental bromine and immediately dissolving same in appropriate volumes of distilled water to yield the required disinfection dosage. Ozone dosing was accomplished through May, 1974 with a Welsbach Ozonator, Model T416. The remainder of ozonation experiments were conducted using a Sander Ozonizer, Type III. Dosing of representative water samples with ozone was calculated to equal the chlorine and bromine dosages. Over periods of time, such as up to 21 days duration in some of the disinfection experiments, one set of water samples were left standing at room temperature and the other set was placed in a Precision Scientific Freas Incubator at 20°C + 1°C. Room temperature was considered to have been 25°C $\pm$ 1°C. All vessels in which the disinfection series samples were placed were sterilized prior to addition of the water. Each vessel was covered with sterilized aluminum foil to retard evaporation and allow oxygen transfer to maintain aerobic conditions.

TABLE 2. SCHEMES USED FOR ISOLATION, IDENTIFICATION, AND ENUMERATION OF SALMONELLA.



XLD - xylose lysine desoxychlate agar
TSI - triple sugar iron agar
API - battery of 21 biochemical tests for classification of the family Enterobacteriaceae

BLENDING

Blending of samples was performed to determine the effect on colony counts. The commercial laboratory blender which was used was a Waring Model 7010S (formerly Model 5010S), 480 watt, 120 volt, 60 H_z and 17,500 rpm base, with four blades. Two blades pitched up at 30° with the horizontal were 2.562 inches and the two blades pitched down at 25° to the horizontal plane were 2.375 inches in length. Each blade was designed to serve as an inverted air foil having a 0.008 inch invert from the leading edge.

STATISTICAL ANALYSES

Multiple regression analyses appeared to have been the most appropriate method for data analysis. To that purpose, a package included in Statistical Package For The Social Sciences (25) was used. The program incorporated a stepwise multiple regression for selecting the dependent variable with the highest predictability combined with the least number of independent variables. Prediction equations were developed and are presented below.

Other programs used included REGRESSION, ANOVA, ONEWAY, SCATTERGRAM, FREQUENCIES, and an analysis of covariance (courtesy Dr. Arthur Littell, Professor of Biometry, U.T. S.P.H.). The University of Texas at Houston Education and Research Computer Center facilities were used with a Control Data Corp. Model No. CYBER 73 having been the instrument employed.

STORM SAMPLING EQUIPMENT

Four stations in the Woodlands were used for storm analyses. The stations and equipment located at each are described below:

1. Station P-10: U.S.G.S. Station No. 08068400. Discrete sampler; Stevens Type A recorder for stage height and manometric water level sensor.

2. Station P-30: Similar to those described for P-10. U.S.G.S. Station No. 08068450.

3. Lake B: U.S.G.S. Float gage with stilling well for stage height, on bridge over Swale 8, Manning S-4000 discrete sampler.

4. Lake A: U.S.G.S. float gage with stilling well for level and a Sigmamotor WM24-R sampler on a pier adjacent to the Lake overflow-weir.

A more detailed description of stormwater sampling procedures can be found in the water quality report to the U.S. Environmental Protection Agency by Rice University, Environmental Science and Engineering Department: Dr. W. G. Characklis, Principal Investigator (Contract No. R802433).

SETTLING EXPERIMENT

To test the effects which the settling of suspended solids had on bacterial densities, equal volumes of a single sample were placed in 5-gallon carboys. One was shaken continuously throughout the test period and the second was left unagitated. Samples were drawn from a depth of 15 cm in all instances.

SECTION 5

RESULTS AND DISCUSSION

SINGLE SAMPLE VARIABILITY AND DIURNAL STREAM STUDY

Ten replicates were plated from a single water sample obtained from station P-02 and analyzed for TC, FC, FS, PS, ST, and SA. The purpose was to determine variances within populations within a shaken water sample. The results of those analyses are summarized below. Units are number/100 ml except FC/FS and $\sigma/\bar{X}$. Number of replicates = 10.

	Mean ($\bar{X}$)	Std. Dev., (σ)	$\sigma/\bar{X}$
Total Coliform	60,836	12,805	21
Fecal Coliform	484	127	26
Fecal Streptococci	796	107	13
FC/FS	0.63	0.22	35
Salmonella sp.	5,310	1,208	23
Staphylococcus sp.	22,718	2,012	9
Pseudomonas aeruginosa	420	86	20

These data are significant in that they represent the variability which can be anticipated within any water sample subjected to analysis for the indicated species and groups of bacteria and at those concentrations. Variability in bacterial populations in a stream over a period of 24 hours during low flow conditions are summarized below. The values were obtained from station P-10; number of samples = 18. Units are number/100 ml except FC/FS and $\sigma/\bar{X}$.

	Mean ($\bar{X}$)	Std. Dev., (σ)	$\sigma/\bar{X}$
Total Coliform	56,611	40,478	71
Fecal Coliform	164	127	77
Fecal Streptococci	227	65	29
FC/FS	0.8	0.9	--
Staphylococcus sp.	287	195	68
Pseudomonas aeruginosa	258	325	126
Salmonella sp.	554	532	96

Concurrently, station P-30 was sampled and the results of those analyses are summarized below. Units are the same as those above. Number of samples = 23.

	Mean ($\bar{X}$)	Std. Dev., (σ)	$\sigma/\bar{X}$
Total Coliform	80,696	20,379	26
Fecal Coliform	213	66	31
Fecal Streptococci	213	237	111
FC/FS	1.3	1.2	--
Staphylococcus sp.	792	582	73
Pseudomonas aeruginosa	185	123	66
Salmonella sp.	279	188	67

Those data suggest that interpretation of data derived from a single grab sample should reflect the conditions of a stream only at the point in time and location from which the sample was obtained. The percentage variability ($\sigma/\bar{X}$) within all of the indicated groups and species was higher at both stations throughout the 24-hour period than within a single sample.

BLENDING OF SAMPLES

The results of blending samples of prechlorinated secondary treated municipal wastewater indicate that all three indicator groups exhibited more than double the counts at the ten second blending interval but order of magnitude differences were not in evidence. In some cases, longer blending times resulted in lower counts than the controls. Blending of samples for disruption of bacterial clumps is impractical for stormwater samples because of the large number of samples taken during each storm event and the time limitation of sterilizing a blender between each sample and the time limitation for plating the samples before each becomes invalid. This blending experiment was requested by U.S.E.P.A. personnel. The data are presented below.

	Blending Time, Seconds					
	0	10	20	40	60	90
Total Coliform, No./100 ml x 10^9	1.4	3.2	1.3	1.3	2.0	1.9
Fecal Coliform, No./100 ml x 10^8	2.8	6.4	1.9	2.9	3.1	5.1
Fecal Streptococci, No./100 ml x 10^4	4.9	7.3	4.7	6.0	5.4	4.2

SEDIMENTATION EXPERIMENTS

Settling experiments were conducted to determine the extent of reduction in bacterial densities in the water column over time. Data obtained for a settling time of 30 minutes using water samples taken from stations S-10 and P-20 are summarized below for the three indicator groups. Units are as number/100 ml.

Station S-10	TC	FC	FS
Agitated	2.17×10^5	7.37×10^4	7.3×10^2
Settled	0.5×10^5	0.36×10^4	6.8×10^2
Station P-20			
Agitated	3.1×10^4	3.0×10^3	9.7×10^2
Settled	1.6×10^4	2.8×10^3	5.1×10^2

The settling rates of the indicator groups differed between the two samples taken from different locations. Suspended solids concentrations probably influenced the results.

In a repeated experiment which included pathogen quantification and settling times up to 12 hours, indicator bacteria did not demonstrate clearly defined settling patterns and FC/FS values were irregular. Pseudomonas (PS) and Salmonella (SA) did not effectively settle whereas Staphylococcus (ST) decreased in numbers within the water column. The results suggest that water samples containing elevated quantities of settleable solids (>200 mg/l), will exhibit low counts if not shaken immediately prior to sampling and plating.

MUNICIPAL WASTEWATER BACTERIOLOGY

Fourteen samples were obtained over a period of as many days of untreated, secondary treated, and chlorinated secondary treated municipal wastewater. They were taken from two of Houston's largest and most efficiently operated treatment plants. These tests were requested by U.S.E.P.A. personnel in order that comparisons could be made with stormwater bacteria densities in the same geographical locale. The data obtained from the analysis of those samples are summarized below. Units are number/100 ml except FC/FS and $\sigma/\bar{X}$ (coefficient of variation).

	Mean ($\bar{X}$)	Std. Devl., (σ)	$\sigma/\bar{X}$
	Untreated Wastewater		
Total Coliform	41.24×10^7_6	101.11×10^7_6	245
Fecal Coliform	30.05×10^6_5	68.86×10^6_5	229
Fecal Streptococci	18.83×10^5	20.72×10^5	110
FC/FS	12.8	9.3	---
	Prechlorinated Secondary Treated Wastewater		
Total Coliform	16.26×10^5_4	13.56×10^5_4	83
Fecal Coliform	27.66×10^4_3	44.88×10^4_3	162
Fecal Streptococci	30.69×10^3	75.56×10^3	246
FC/FS	126	64	---
	Chlorinated Secondary Treated Wastewater		
Total Coliform	245.7	318	130
Fecal Coliform	18.1	24.9	137
Fecal Streptococci	6.7	9.5	142
FC/FS (n=7)	1.5	0.7	---

Perhaps the most striking result is the indicated change in FC/FS. The chlorinated effluent FC/FS ratio of 1.5 suggests the pollutant source to have been of mixed origin (man and other animals). Prechlorinated secondary treated indicator bacteria densities were within levels observed in storm water populations. Ten additional samples were analyzed in order to compare pathogen densities with indicator bacteria densities. The data for these ten analyses are summarized as follows; values are for number/100 ml.

	Mean ($\bar{X}$)	Std. Dev., (σ)
	Untreated Wastewater	
Total Coliform	59.07×10^8	135.76×10^8
Fecal Coliform	32.66×10^5	45.75×10^5
Fecal Streptococci	5.1×10^5	1.51×10^5
Pseudomonas aeruginosa	1.69×10^5	1.41×10^5
Staphylococcus sp.	2.79×10^5	2.13×10^5
Salmonella sp.	7.98×10^3	19.72×10^3
	Prechlorinated Secondary Treated Wastewater	
Total Coliform	44.87×10^6	94.80×10^6
Fecal Coliform	3.17×10^5	1.68×10^5
Fecal Streptococci	1.35×10^4	0.49×10^4
Pseudomonas aeruginosa	2.66×10^3	1.71×10^3
Staphylococcus sp.	3.54×10^4	4.92×10^4
Salmonella sp.	1.40×10^2	2.00×10^2

	Mean ($\bar{X}$)	Std. Dev., (σ)
	Chlorinated Secondary Treated Wastewater	
Total Coliform	2.73×10^2	6.19×10^2
Fecal Coliform	41.8	125.9
Fecal Streptococci	140.0	263.3
Pseudomonas aeruginosa	2.8	4.1
Staphylococcus sp.	3.74×10^2	4.68×10^2
Salmonella sp.	ND	ND

(ND = none detected)

Salmonella sp. were not detected in 50 ml of sample. The chlorination apparently resulted in the virtual elimination of Salmonella sp. but permitted substantial numbers of total coliforms to survive. It was least effective against staphylococci.

SAMPLE PRESERVATION STUDY

The effect of storage temperature on the bacterial content of samples was important for data analysis due to travel time and sampling intervals during storm events. The samples were obtained from station P-30 on January 11, 1976. The data derived from the analyses of all bacterial groups and species are summarized below as the mean values of five replicates at each of the three times. Units are number/100 ml.

	Time, Hrs. 0	6	12
	Stored at 20°C		
Total Coliform	1.65×10^5	1.71×10^5	1.63×10^5
Fecal Coliform	2.29×10^2	2.20×10^2	2.34×10^2
Fecal Streptococci	2.45×10^3	2.56×10^3	2.73×10^3
Pseudomonas aeruginosa	3.48×10^4	3.46×10^4	3.10×10^4
Staphylococcus sp.	1.16×10^3	1.18×10^3	1.11×10^3
Salmonella sp.	1.9×10^2	1.7×10^2	1.8×10^2
	Stored at 4°C		
Total Coliform	1.67×10^5	1.62×10^5	1.80×10^5
Fecal Coliform	2.51×10^2	2.66×10^2	2.40×10^2
Fecal Streptococci	2.62×10^3	2.37×10^3	2.39×10^3
Pseudomonas aeruginosa	3.53×10^4	3.52×10^4	3.02×10^4
Staphylococcus sp.	1.36×10^3	1.38×10^3	1.42×10^3
Salmonella sp.	2.0×10^2	1.9×10^2	2.2×10^2

A statistical analysis (t-test) indicated that the only significant difference was found with Pseudomonas aeruginosa. The standard deviation was lower, however, than those calculated for the variance within a single sample; the data for which have been presented above. It is important to note that the greater average decrease in Pseudomonas aeruginosa concentration occurred in the refrigerated sample. In all probability the differences are not significant when compared to field sampling variations.

SOIL AND SEDIMENT ANALYSES

An important factor in the bacterial contamination of waterways during and following storm events is the stream sediment bacterial content, content of soils in adjacent areas and stream velocity. Other investigators have reported similar sources of contamination.

Contaminated soils yield erratic leaching concentrations of indicator bacteria. This variance depends on amount and duration of rainfall. A 90% reduction for FC was reported to have been attained in 3.3 days in summer and 13.4 days in the fall (26). For the fecal streptococci the same report indicated a 90% reduction in numbers in a time of 2.7 days in the summer and 20.1 days in winter. Heavier and prolonged rains yielded greater numbers of isolates than short duration rainfall events. Longer survival periods have been reported by Mallman and Litsky (27). Their investigation involved soils with elevated organic contents. At up to eleven weeks duration the log number/100 grams of soil ranged from 5.6 at time zero to 3.2 at eleven weeks. Livestock were observed grazing in some undeveloped areas of the primary test site periodically throughout this investigation. Therefore it is entirely possible that considerable numbers of indicator bacteria and pathogens were contributed to the water courses from those sources. Soils and stream sedimentary materials were analyzed for their bacterial content in order to determine whether contributions to overlying waters during periods of heavy rainfall or elevated stream volumes were made from those sources. Von Donsel and Geldreich (28) demonstrated that distinct relationships exist between pollution and FC and FS in the top two inches of mud. FC were found to have been 100-1,000 times as concentrated in the mud as in the water. A 19% probability for isolating SA in muds existed when the FC were at concentrations of 1-200/100 ml in the water. The probability increased to 80% for SA in the mud when the FC were at levels exceeding 2,000/100 ml in the water. Human population density also influences runoff coliform densities. Söderlund and Lehtinen (29) found that at a density of 35 persons/ha, the stormwater runoff contained 3.7×10^{11}/100 ml and at 100 persons/ha the coliforms were 9.2×10^{11}/100 ml.

The effect of suspended sediment as a major source of bacterial contamination during such periods was determined by sampling the stream sediment and soils in the vicinity of the established sampling stations during low flow periods. The results of those analyses are summarized below. Units are number/gram of sediment or soil.

	Stream Sediment	Soils	Lakes A&B Sediment
Total Coliform	$100\text{-}31x10^4$	200-3,500	1,000-25,000
Fecal Coliform	<20-20	<20-40	20-60
Fecal Streptococci	<20-20	<20-340	45-270
Pseudomonas aeruginosa	<20-20	<20-40	100-500
Staphylococcus sp.	20-240	160-1,000	15-2,600
Salmonella sp.	<25	<25	<25

Soil samples from the golf course area, swales, wooded areas, and near roads exhibited the following bacterial contents. Units are number/gram.

	Ranges
Total Coliform	1,000-543,000
Fecal Coliform	<20-280
Fecal Streptococci	<20-1,000
Pseudomonas aeruginosa	<20-1,000
Staphylococcus sp.	40-1,040
Salmonella sp.	<25

Since the samples were obtained from the first two inches (5 cm) of soil or sediment cover, leaching and scour velocities obviously could have contributed to elevated bacterial concentrations during storm events.

LOW FLOW MONITORING

The principal value of the data derived from monitoring low flows is for comparison purposes with either urban stream quality or storm event data developed from the primary test site. More specific results for those low flow data are included in statistical analysis results which are included at the end of this section.

Concentrations of indicator bacteria and pathogens ranged far beyond the diurnal low flow variation values and single sample variations during the period of survey. The ranges are summarized below. Units are number/100 ml.

	Range
Total Coliform	$200\text{-}10x10^6$
Fecal Coliform	<10-214,000

	Range
Fecal Streptococci	<10-1,580
Pseudomonas aeruginosa	<10-53,600
Staphylococcus sp.	1-23,400
Salmonella sp.	1-5,800

The maximum values are comparatively high for a rural forested area receiving no direct sewage discharges.

Figure 3 presents some of the earlier data representing the relationships between TC vs FC and FS for values obtained from analyzing station P-20 waters. Statistically, the slopes of each are not that dissimilar. Visual analyses of those least square data fit lines indicate a comparatively low rate of either FC or FS with corresponding increases in TC.

Comparisons were made of low flow FC data with existing contact and non-contact recreational standards. Recalling that the geometric mean values not to be exceeded for contact recreation are 200/100 ml ($\log_{10}$ = 2.3) and for non-contact recreation are 2,000/100 ml ($\log_{10}$ = 3.3) on the basis of 5 samples taken in 30 days, the following relationships are present in the low flow data. At station P-10 the mean value for all low flow data was 2.13 ($\log_{10}$ basis). That implies that, on the average, no values for FC exceeded the contact recreation standard. For stations P-30, Lake A and Lake B, the values can best be discussed by the following summary.

	Station P-30	Lake B	Lake A
Geometric Mean	2.38	1.98	1.53

Waters at station P-30, therefore, were unacceptable for contact recreation whereas the lakes seemed to effect reduction in FC values.

CHARACTERISTICS OF IMPOUNDMENTS IN THE PRIMARY TEST SITE

Field measurements for dissolved oxygen, pH, temperature and light penetration were made in Lakes A and B when top (0.3m) and bottom water samples were taken on five dates: 1/11/75; 10/19/75; 12/15/75; 1/24/76; and 2/15/76. Sampling points are represented in Figure 2. The numbers of sample sites varied, but was never fewer than four in Lake B and six in Lake A.

Physically, both impoundments remained highly turbid during periods of low flow. Runoff from swale 8, entering Lake B, thence to Lake A always contained colloidal materials which tended not to settle. Early in the survey of the lakes it became obvious that both impoundments were operating

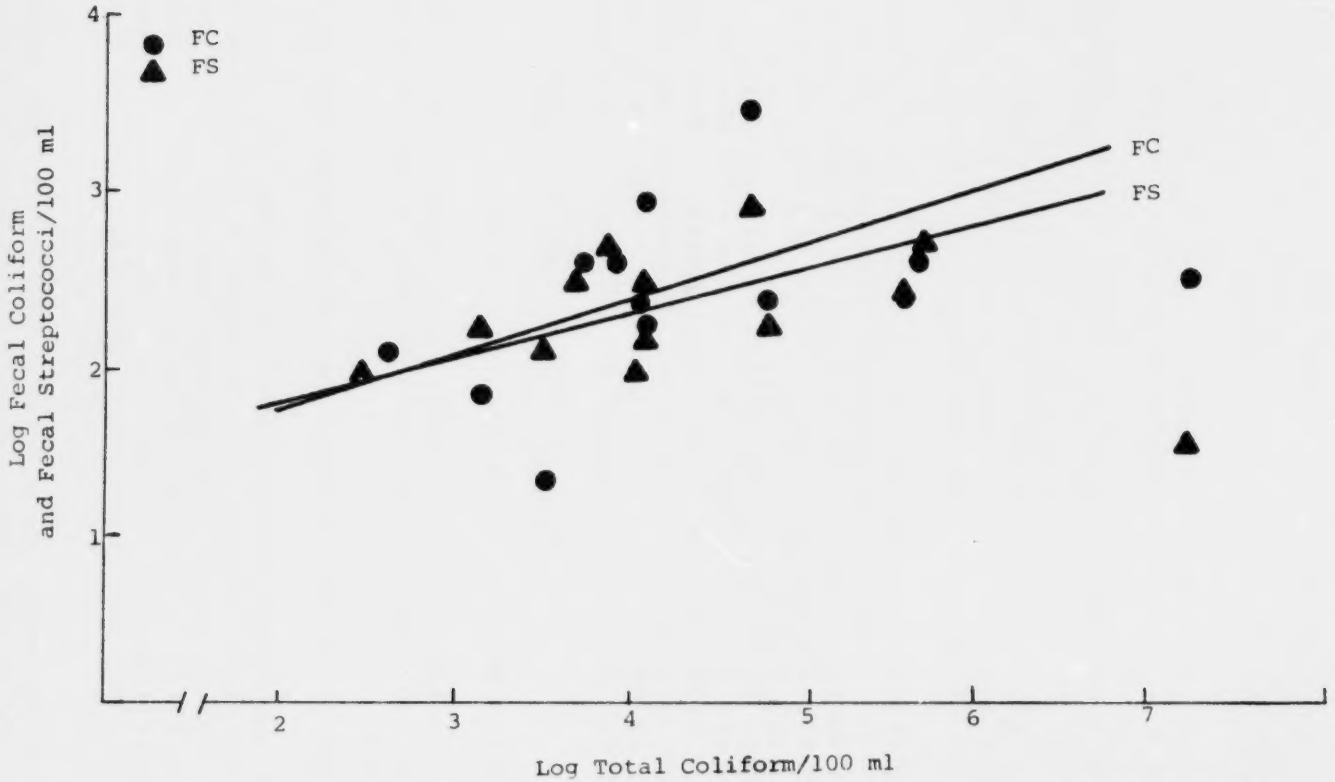


Figure 3. Total coliform vs fecal coliform and fecal streptococci relationships during low flow periods. Station P-20.

hydrologically as sedimentation basins. This can be justified by comparing most of the data for the upper reaches of Lake B with the data for Lake A (Table 3.) Turbid conditions can easily be verified by the quoted Secchi Disc values; those generally were less than a foot. Dissolved oxygen concentrations were always found to have been more than adequate to allow survival of the fish species which were stocked in the impoundments. pH values usually ranged from 7.8 to 8.4. A peculiar bacteriological characteristic of both impoundments was the relatively low densities of FC, FS, and all pathogens whereas the TC values were high. That pattern of behavior implies that TC enumeration, used as a water quality evaluation tool, is almost meaningless if considered alone. Although the FC mean log values were 1.98 and 1.53 during low flow conditions for Lakes B and A, respectively, for FC, another view of the data on a direct mathematical basis merits other attention. Thirty-nine of 104 FC data or 37.5% exceeded the 200/100 ml standard.

STORMWATER DISINFECTION REQUIREMENTS

Disinfection of combined sewers and stormwater has been used but may not be, in itself, the final answer to pollution control. Glover and Herbert (30) found that 5 mg/l chlorine additions in high rate chambers reduced "coliforms" by four or more orders of magnitude. Initial FC and FC levels reported were 0.1×10^6 to 3×10^6/100 ml and 1×10^3 to 1×10^5/100 ml respectively. Final FC levels were 5-10/100 ml. Some regrowth may occur in those instances if complete die-off is not attained. Reports from other areas of the country (31, 32) showed combined sewer overflows to have contained indicator bacteria at the following levels: TC, 11×10^6/100 ml and FC, 1.6×10^6/100 ml. FC levels in combined sewer flows ranged from 7.5×10^3 to 1.6×10^7 in dry weather and 1.2×10^1 to 2.0×10^7 in wet weather (32). It must be remembered though that the character of combined sewers and stormwater runoff alone is not necessarily the same.

Disinfection of stormwater is feasible and it is generally agreed that large dosages will be required to achieve adequate reduction in indicator and pathogen densities. Chlorine or chlorine dioxide has been reported to be the most effective disinfectant, and in many cases the least expensive (33, 34, 35). Davis, et al. (36, 37) discussed current disinfection research and practices along with encountered problems which occur in combined sewer disinfection and stormwater disinfection.

Samples were obtained from different locations during low flow periods and during storm events to determine the disinfectant demand and the disinfection effectiveness.

TABLE 3. PHYSICAL, CHEMICAL, AND BACTERIAL RANGES IN LAKES A AND B. VALUES ARE FROM SURVEYS OF 1/11/75, 10/19/75, 12/15/75, 1/24/75, and 2/15/76.

	Lake B	
	Surface	Bottom
Diss. Oxygen, mg/l	8.0-8.5	7.6-8.0
pH	7.8-8.4	7.6-8.0
Temp., °C	13.5-22.5	13.0-23.8
Secchi Disc, inches	3-14	----
Total Coliform, No./100 ml	$1x10^3$-$1.09x10^6$	$2x10^3$-$2.34x10^5$
Fecal Coliform, No./100 ml	60-$97x10^3$	90-$1.09x10^3$
Fecal Streptococci, No./100 ml	100-$2.85x10^3$	100-$1.7x10^3$
Pseudomonas aeruginosa, No./100 ml	<10-$9.0x10^4$	<10-$5.5x10^5$
Staphylococcus sp., No./100 ml	<10-600	400-$1.6x10^3$
Salmonella sp., No./100 ml	25-100	25-500
	Lake A	
Diss. Oxygen, mg/l	8.0-8.5	6.3-7.0
pH	7.7-8.3	7.5-8.2
Temp., °C	13.0-23.8	13.5-21.5
Secchi Disc, inches	3-12	----
Total Coliform, No./100 ml	$2x10^3$-$1.4x10^5$	$3x10^3$-$2.9x10^5$
Fecal Coliform, No./100 ml	80-820	160-400
Fecal Streptococci, No./100 ml	10-$1.35x10^3$	100-$2.47x10^3$
Pseudomonas aeruginosa, No./100 ml	<20-1,980	<10-1,930
Staphylococcus, sp. No./100 ml	300-700	100-800
Salmonella sp., No./100 ml	<10-20	<10-30

Locations from which the water samples were taken and other pertinent data are summarized below.

Date	Disinfectant	Station(s)
12/6/73	Cl_2	P-20
1/15/74	Cl_2	P-30, S-10 (and Cl_2 demand)
4/22/74(storm)	Cl_2, Br_2, O_3	P-30
12/5-9/74(storm)	Cl_2	P-30
3/12-14/75(storm) (Multiple Times)	Cl_2, O_3	Lake A
3/13/75	Cl_2, O_3	Lake A (and Cl_2 demand)
4/7-10/75(storm) (Multiple Times)	Cl_2, O_3	Lake A
4/7/75	Cl_2, O_3	Lake A (and Cl_2 demand)
5/8-9/75(storm) (Multiple Times)	Cl_2, O_3	Westbury
8/14/75	Cl_2, O_3	Woodlands (Sew, Treat. Plant)
11/26/75(storm) (Multiple Times)	Cl_2, O_3	Westbury

Those samples termed "multiple times" in the above list signify that disinfection was applied to separate samples taken at different times throughout storm events. The purpose for that approach was to determined whether the qualities of water discharged throughout a storm event required different amounts of disinfectant to achieve the same end product. Examination of those data revealed that little, if in fact any difference in the disinfectant requirement between times in storms occurred. The reason for that was the large disinfectant demand of the storm waters. That demand was due for the most part to high solids (and turbidity) values; values exceeding 200 mg/l solids. Data from disinfection experiments were averaged for those dosages and points in time which were common to each set. They are presented in graphical summary form following these commentaries.

Chlorine demand varied from station to station. The data indicated the waters at station S-10 had a demand of about 8 mg/l and those at station P-30 had a demand of between 8 and 16 mg/l. The chlorine demand of Lake A waters on 3/13/75 was 10 mg/l and the ozone demand was in excess of 32 mg/l. Other data indicated the same demand for Lake A outflow waters from 4/7/75 and for 3/13/75 samples. Demands such as those may result in the disinfection of storm waters being an economically unwise and unfeasible venture except in specific instances where impairment of the public health is foreseen.

It therefore becomes a matter of choice on a location and need basis.

Summary disinfection data presented in Figures 4 through 7 relate basically six complete disinfection sequences with chlorine. TC concentrations tended to increase from 5.0 (log value) to 5.1 in the control over the eight day test period. FC and FS concentrations decreased from 2.4 to 1.2 (FC) and 3.6 to 1.8 (FS) in 8 days. Staphylococci proved to be the longer lived of the three pathogens which were enumerated; decreasing from 2.9 (log value) to 2.2 in eight days. PS and SA demonstrated viability at eight days but were present at time zero in relatively low concentrations. Pathogens at log No./100 ml values of 1.0 were at the lower detection limit. Some data for those groups showed values of $<1 \times 10^1$.

With chlorination at 2, 4, 8, and 16 mg/l dosages the TC all responded similarly, i.e., a decrease at 30-minutes followed by regrowth of from about 2 (log value) to about 7. All chlorine dosages effectively reduced the FC and FS populations to about 10/100 ml within one day. They remained at that level for 8 days. ST showed initial decreases with all chlorine dosages to minimum values at one day, then regrowth to about 4 days, followed by dieoff similar to the controls. PS and SA demonstrated almost no propensity for aftergrowth following all chlorine doses. Figures for SA values are not included. They were at or below detection concentrations.

Indicator and pathogen figures are not included for ozone due to the fact that they would appear to be near duplication of the chlorine dosages. For all practical purposes the behavior of the bacteria in the presence of ozone was similar in all but one case. That exception was some regrowth of FS from 4 to 8 days following 8 mg/l O_3 dosage.

TC populations which reestablished themselves to higher concentrations than the control at 8 days, did so, perhaps, due to decreases in competitive populations of other bacteria. FC and FS were unable to compete at such low population densities and therefore did not demonstrate aftergrowth potentials. Staphylococci on the other hand demonstrated the ability to increase in numbers up to 4 days time. That pattern was followed by normal dieoff in the reestablished populations. Graphs were not constructed for PS and SA because of their relatively simplistic responses. FS, for example, decreased to about 10/100 ml at all chlorine doses and remained at that level, along with the control population to 8 days. SA dropped to or below detection levels (1/100 ml

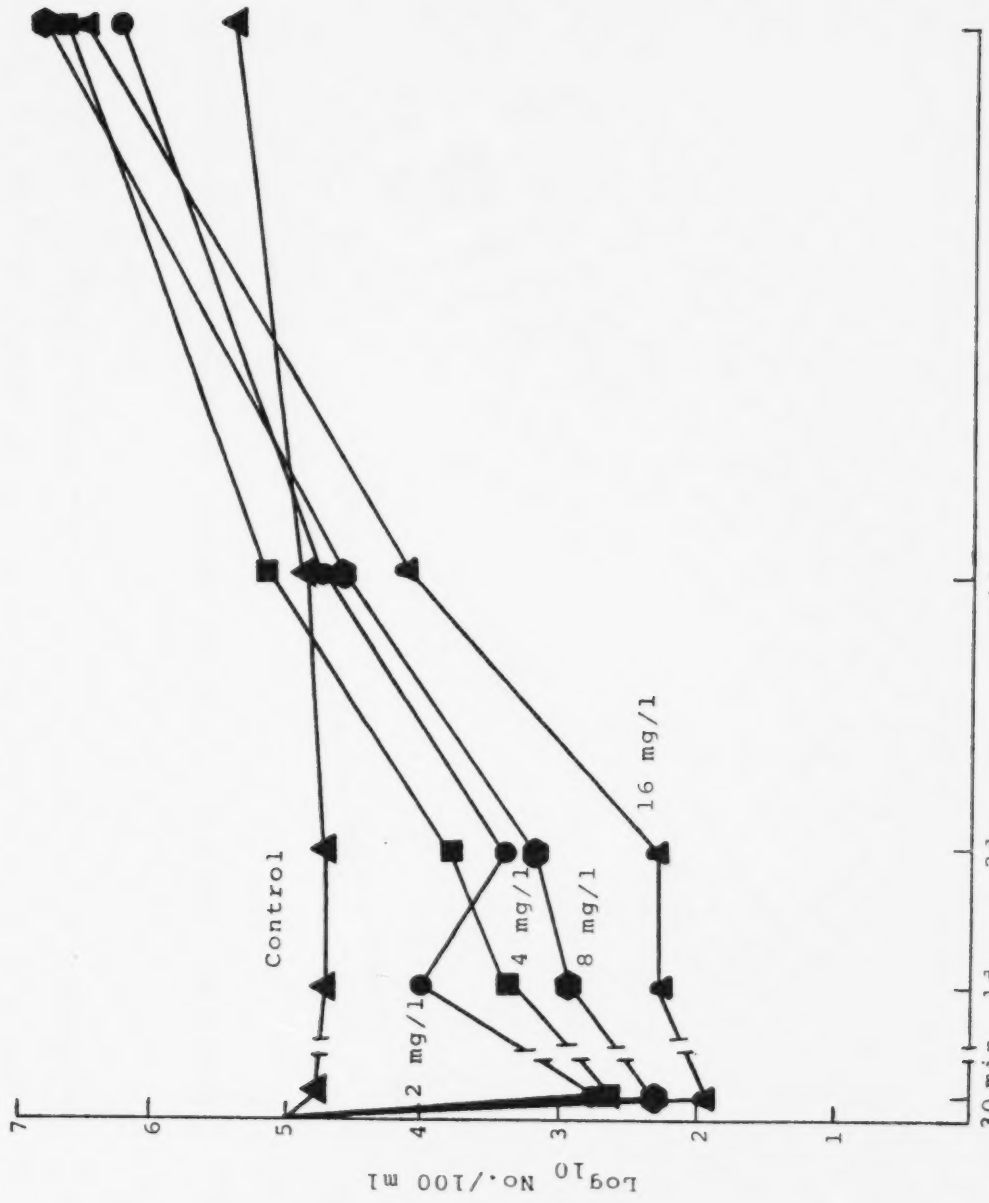


Figure 4. Total coliform responses to chlorine; Lake A (n=6).

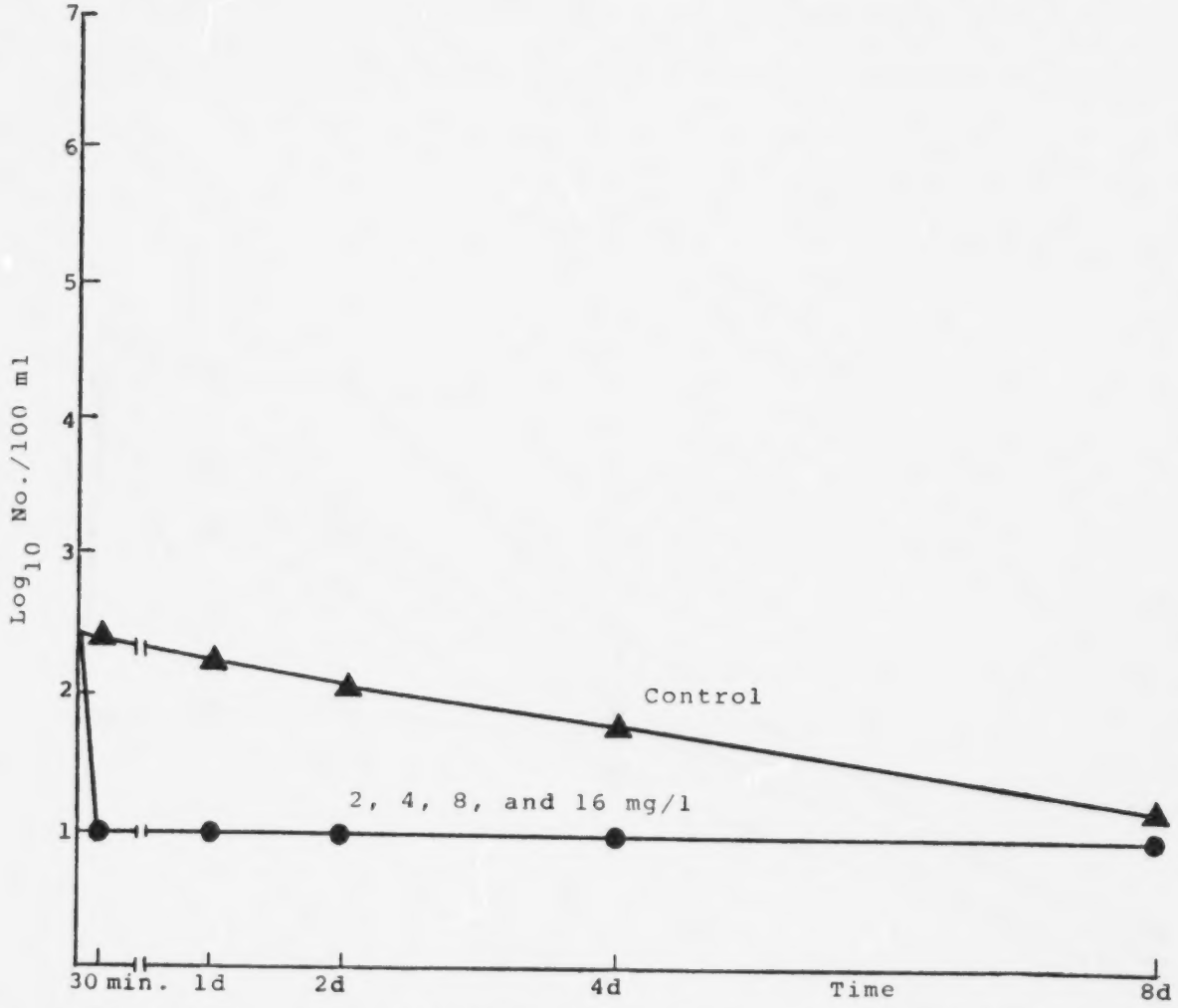


Figure 5. Fecal coliform responses to chlorine; Lake A (n=6).

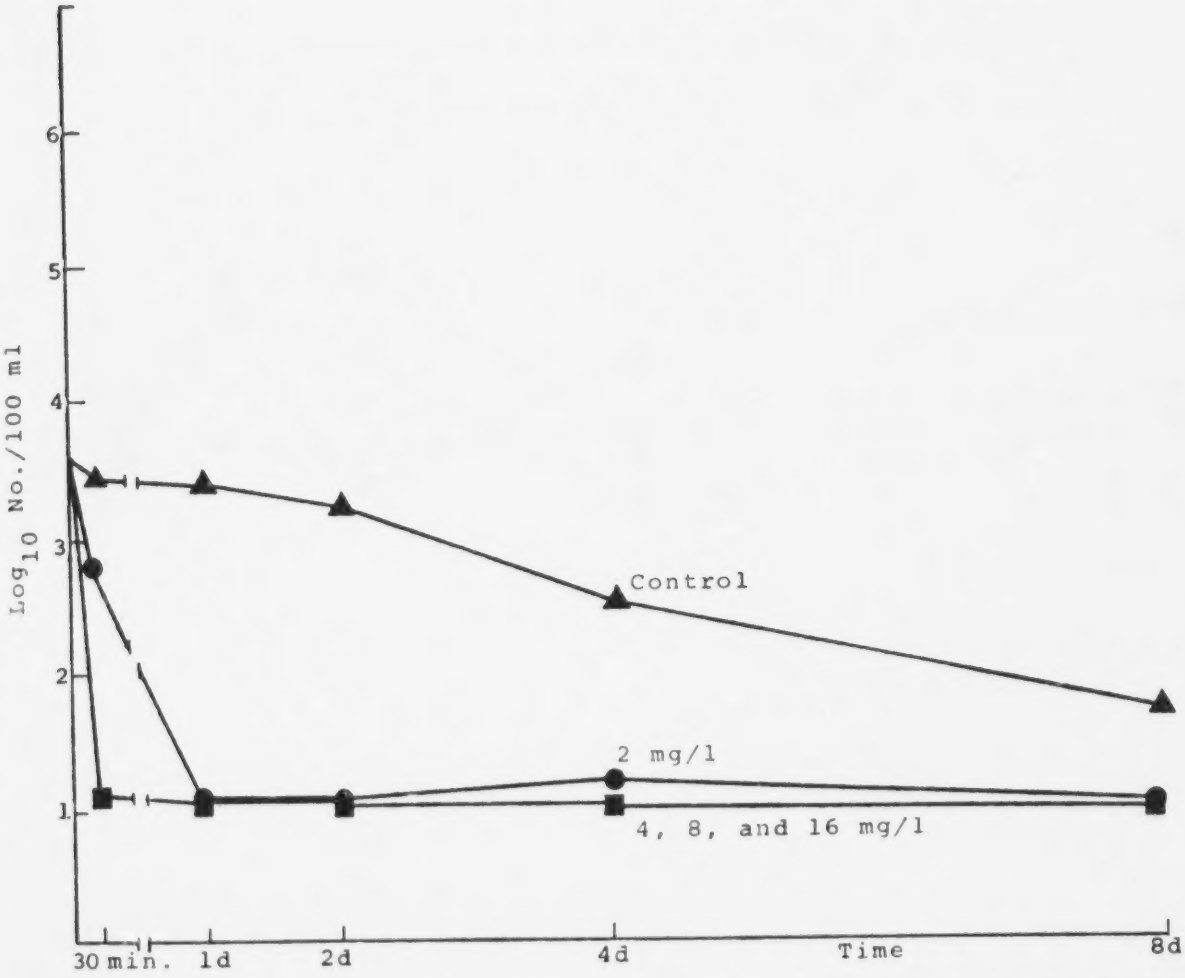


Figure 6. Fecal streptococci responses to chlorine; Lake A (n=6).

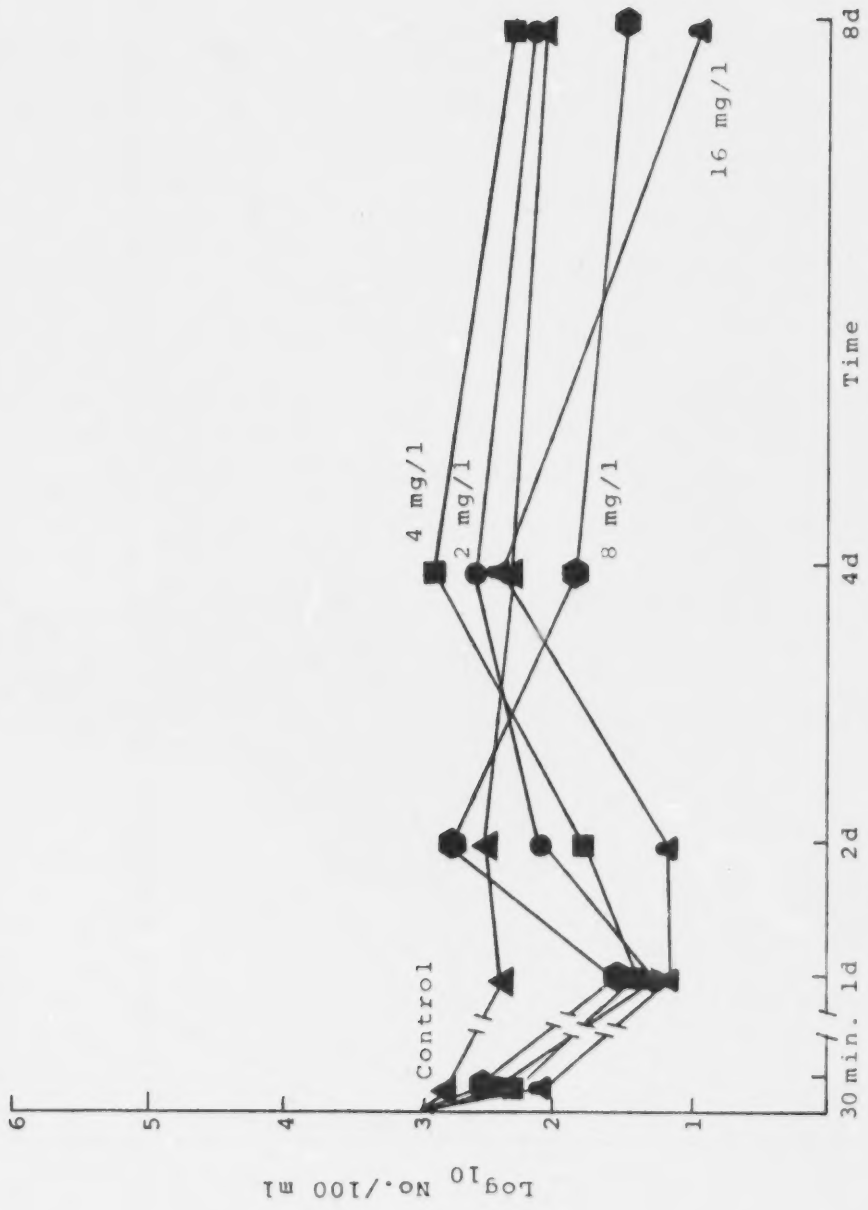


Figure 7. Staphylococci responses to chlorine; Lake A (n=6).

or less) almost immediately following chlorination and remained at those densities throughout the 8-day test period.

STORM EVENT MONITORING

Twenty-one storm events were monitored for microbiological content. The dates and locations from which samples were obtained are summarized below.

Date	Location	Stations Monitored
1/19-20/74	Woodlands	P-30
3/20-21/74	Hunting Bayou	Single
3/27-28/74	Hunting Bayou	Single
4/11-12/74	Hunting Bayou	Single
4/22-23/74	Woodlands	P-30
4/22-23/74	Woodlands Summary	P-30
10/28-31/74	Woodlands	P-30
12/5-9/74	Woodlands	P-10, P-30
3/4/75	Woodlands	P-30, Lakes A&B
3/12-14/75	Woodlands	P-10, P-30, Lakes A&B
4/7-10/75	Woodlands	P-10, P-30, Lakes A&B
5/8-9/75	Hunting Bayou	Single
5/8-9/75	Westbury	Single
6/30-7/1/75	Hunting Bayou	Single
6/30-7/1/75	Westbury	Single
9/5-6/75	Woodlands	P-10, P-30, Lakes A&B
10/25-27/75	Woodlands	P-10, P-30, Lakes A&B
11/26/75	Westbury	Single
3/7-8/76	Woodlands	P-10, P-30, Lakes A&B
3/8-9/76	Woodlands	P-30, Lakes A&B
4/5/76	Woodlands	P-10, P-30, Lakes A&B

In examining the data representing the storm events monitored at the Hunting Bayou site it was discovered that the TC values were not dissimilar from values reported from other test sites. The TC range of all reported values for Hunting Bayou water samples was from 3.1×10^4 to 7×10^8. That upper limit was an order of magnitude higher than most values from all other locations. Those data are included in the statistical evaluation of different land use areas which is discussed in a following subsection. Data obtained from Hunting Bayou are summarized below.

Storm	TC, log No./100 ml Min.	Max.	Time at Max., Hrs.	No. of Samples
3/20/74	4.49	5.48	1.75	13
3/27/74	4.86	6.45	9.5	67
5/8/75	7.00	8.84	ND	27
6/30/75	4.78	6.70	ND	35

Peaking times were not discernable for the latter two storm events because of high variances in the water samples. For the most part, the TC concentrations were at high levels and remained at those levels throughout the period of time the waters were monitored.

Westbury site waters demonstrated similar trends in TC concentrations as well as within the other groups and species. Data representing the three storm events monitored at that site are as follows (TNTC = Too Numerous To Count):

		log No./100 ml		
Storm		Min.	Max.	Mean
5/75	TC	4.70	8.70	7.48
(n=11)	FC	3.86	4.60	4.34
	FS	2.60	4.61	4.12
	PS	2.30	4.40	3.88
	ST	3.07	4.30	3.91
	SA	<1.51	<1.51	<1.51
6/75	TC	4.47	8.70	7.48
(n=12)	FC	2.93	4.60	4.34
	FS	2.83	4.61	4.12
	PS	2.97	4.40	3.88
	ST	3.43	4.30	3.91
	SA	<1.40	<1.51	<1.51
11/75	TC	6.26	6.67	6.49
(n=5)	FC	3.96	4.50	4.28
	FS	4.39	4.68	4.51
	PS	4.31	TNTC	4.54
	ST	TNTC	TNTC	--
	SA	2.00	4.17	3.19

Points in time at which peaking occurred for TC, FC, and FS were impossible to determine because the concentrations tended to demonstrate continual increases throughout the time of monitoring each storm event. In the cases of PS, ST, and SA, extremely high variances occurred between samples. Generally, most of the groups or species measured were at or above those minimum base level concentrations and maximum (peak) concentrations for Woodlands storm events.

Woodlands sites demonstrated more constancy in peaking trends for both the bacterial concentrations and physical factors. This can be observed in the data presented in Tables 4 and 5. Pathogens are not included for the 1/18/74 and 4/22/74 storms at station P-30 because the identities of those which needed the greatest amount of attention (PS, ST, SA) were not determined at that time. Times at which bacterial peaking occurred are indicated in Table 4 for comparison with hydrograph peaks, and solids and turbidity peaks in Table 5. The notation "ND" signifies discernable peaks were not detectable from the available data. That happened most often

TABLE 4. SUMMARY OF INDICATOR AND PATHOGEN BASE LEVELS, PEAK LEVELS AND TIMES DURING STORM EVENTS.

Station	Indicator	Log of No./100 ml Min.	Max.	Mean	Time @ Max., Hrs.	Station	Indicator	Log of No./100 ml Min.	Max.	Mean	Time @ Max., Hrs.
1/18/74	TC	3.95	5.37	4.92	5	12/5/74	TC	4.48	6.02	5.38	3
P-30	FC	2.75	4.32	3.63	8	P-30	FC	2.60	4.28	3.86	3
	FS	2.45	4.30	3.61	8		FS	2.00	4.24	3.48	3
	PS	--	--	--	-		PS	2.00	3.00	2.87	3
	ST	--	--	--	-		ST	2.90	3.80	3.45	4
	SA	--	--	--	-		SA	1.52	2.42	1.94	2
4/22/74	TC	6.00	7.76	7.15	13	12/5/74	TC	4.00	6.32	5.13	5
P-30	FC	2.20	4.13	3.89	8	P-10	FC	2.00	4.06	3.20	18
	FS	1.95	4.33	3.73	14		FS	2.00	3.46	2.65	15
	PS	2.78	4.42	--	8		PS	1.00	2.77	2.15	18
	ST	--	--	--	-		ST	<1.00	3.73	2.77	12
	SA	--	--	--	-		SA	<1.39	2.52	1.88	20
10/28/74	TC	4.78	6.90	5.98	6	3/4/75	TC	4.68	5.61	5.17	-
P-30	FC	2.00	4.65	3.63	9	P-30	FC	2.58	3.32	3.00	-
	FS	2.00	5.15	3.73	5		FS	2.85	4.03	3.37	-
	PS	2.30	4.45	3.46	3		PS	1.48	2.00	1.80	-
	ST	2.00	5.52	3.77	10		ST	2.99	4.16	3.40	-
	SA	1.70	3.40	--	4		SA	<1.40	1.40	<1.40	

TABLE 4. SUMMARY OF INDICATOR AND PATHOGEN BASE LEVELS, PEAK LEVELS AND TIMES DURING STORM (CONT'D.) EVENTS.

Station	Indicator	Log of No./100 ml Min.	Max.	Mean	Time @ Max., Hrs.
3/4/75	TC	5.36	6.03	5.58	1.5
Lake B	FC	1.60	3.90	3.38	1.5
	FS	3.46	4.38	4.21	4
	PS	2.67	3.83	3.39	3
	ST	3.67	4.45	4.12	1
	SA	<1.40	<1.40	<1.40	---
3/4/75	TC	3.85	4.70	4.52	---
Lake A	FC	<1.00	1.30	.85	---
	FS	2.60	3.72	3.16	---
	PS	<1.00	2.43	1.52	---
	ST	1.00	2.74	2.14	---
	SA	<1.40	<1.40	<1.40	---
3/12/75	TC	4.78	6.72	5.99	19
P-30	FC	1.00	3.65	2.41	19
	FS	1.00	3.92	2.49	19
	PS	<1.00	1.85	1.58	19
	ST	2.38	3.89	2.98	22
	SA	<1.40	2.00	1.74	22
3/12/75	TC	4.30	6.57	5.93	18
P-10	FC	<1.00	3.44	2.93	19
	FS	<1.00	3.39	2.87	21
	PS	<1.00	2.69	1.55	ND
	ST	1.00	3.40	2.52	20
	SA	<1.40	2.10	1.53	ND
3/12/75	TC	4.60	6.75	6.18	15
Lake B	FC	<2.00	3.46	3.12	18
	FS	<2.00	3.93	3.53	15
	PS	<2.00	3.58	2.73	18
	ST	2.85	5.23	4.04	18
	SA	<1.40	2.24	1.25	20
3/12/75	TC	4.00	5.49	4.91	20
Lake A	FC	<1.00	2.15	1.44	21
	FS	1.88	3.53	3.12	20
	PS	<1.00	1.95	.47	ND
	ST	1.00	1.95	1.50	17
	SA	<1.40	2.40	1.47	19

TABLE 4. SUMMARY OF INDICATOR AND PATHOGEN BASE LEVELS, PEAK LEVELS AND TIMES DURING STORM (CONT'D.) EVENTS.

Station	Indicator	Log of No./100 ml Min.	Max.	Mean	Time @ Max., Hrs.
4/7/75	TC	3.77	6.80	5.48	21
P-30	FC	2.00	4.40	3.38	14
	FS	2.00	4.42	3.47	16
	PS	<2.00	3.51	2.67	ND
	ST	2.30	3.85	3.26	13
	SA	<1.51	2.12	1.72	ND
4/7/75	TC	4.32	6.79	5.18	20
P-10	FC	<2.00	4.40	3.36	20
	FS	2.00	4.24	3.05	18
	PS	<2.00	3.26	2.35	21
	ST	2.30	3.45	2.88	19
	SA	<1.51	2.36	1.89	23
4/7/75	TC	4.00	5.80	5.25	21
Lake B	FC	2.00	4.39	3.37	16
	FS	2.00	4.40	3.23	14
	PS	2.00	3.57	2.81	14
	ST	2.48	3.83	3.17	13
	SA	<1.51	2.51	.28	ND
4/7/75	TC	4.00	5.62	5.06	ND
Lake A	FC	2.00	3.60	3.03	14
	FS	2.00	4.06	3.50	14
	PS	<2.00	3.36	2.61	ND
	ST	2.30	3.36	3.29	ND
	SA	<1.51	2.00	.35	ND
9/5/75	TC	6.44	6.70	6.58	ND
P-30	FC	3.00	3.60	3.39	ND
	FS	4.59	5.47	5.12	ND
	PS	3.00	4.46	3.72	ND
	ST	3.70	4.43	4.10	ND
	SA	<1.00	<1.00	<1.00	ND
9/5/75	TC	3.90	5.18	4.30	ND
P-10	FC	<1.00	2.78	2.41	ND
	FS	1.60	2.63	2.19	ND
	PS	<1.00	1.90	1.60	ND
	ST	1.00	2.23	1.69	ND
	SA	<1.00	1.00	1.00	ND

TABLE 4. SUMMARY OF INDICATOR AND PATHOGEN BASE LEVELS, PEAK LEVELS AND TIMES DURING STORM (CONT'D.) EVENTS.

Station	Indicator	Log of No./100 ml Min.	Max.	Mean	Time @ Max., Hrs.	Station	Indicator	Log of No./100 ml Min.	Max.	Mean	Time @ Max., Hrs.
9/5/75	TC	6.34	6.86	6.55	ND	10/25/75	TC	5.20	6.02	5.41	4
Lake B	FC	3.48	4.26	3.90	ND	P-10	FC	2.60	4.81	3.48	4.5
	FS	4.41	4.99	4.74	ND		FS	2.20	4.39	3.36	3.5
	PS	4.11	5.12	4.66	ND		PS	1.47	3.97	2.99	3.5
	ST	3.78	5.03	4.42	ND		ST	2.04	3.43	2.68	3
	SA	<1.00	<1.00	<1.00	ND		SA	<1.40	2.17	1.54	2
9/5/75	TC	3.78	4.97	4.28	ND	10/25/75	TC	4.90	6.87	6.01	1.5
Lake A	FC	2.00	2.85	2.36	ND	Lake B	FC	3.20	4.44	4.22	2
	FS	2.04	2.88	2.52	ND		FS	3.30	4.85	4.16	1
	PS	1.46	3.40	2.62	ND		PS	2.60	4.63	3.62	10
	ST	1.50	2.82	2.05	ND		ST	2.47	5.02	4.03	1
	SA	<1.00	<1.00	<1.00	ND		SA	<1.40	2.30	1.40	34
10/25/75	TC	4.00	6.04	5.52	6	10/25/75	TC	3.84	4.99	4.20	1
P-30	FC	3.17	4.62	4.17	9	Lake A	FC	1.00	3.00	2.41	13
	FS	3.14	4.94	4.26	7.5		FS	1.69	3.21	2.88	10
	PS	3.11	4.77	4.34	7.5		PS	1.00	3.66	2.04	16
	ST	2.77	5.05	3.72	7.5		ST	1.00	3.06	2.29	3
	SA	<1.40	2.17	1.62	12.5		SA	<1.40	2.30	.62	56

TABLE 4. SUMMARY OF INDICATOR AND PATHOGEN BASE LEVELS, PEAK LEVELS AND TIMES DURING (CONT'D.) STORM EVENTS.

Station	Indicator	Log of No./100 ml Min.	Max.	Mean	Time Max., Hrs.	Station	Indicator	Log of No./100 ml Min.	Max.	Mean	Time Max., Hrs.
3/7/75	TC	5.30	5.92	--	--	3/7/76	TC	4.30	5.18	--	--
Lake B	FC	3.04	4.80	--	--	P-30	FC	2.78	3.53	--	--
	FS	3.23	3.79	--	--		FS	3.18	3.72	--	--
	PS	2.30	3.04	--	--		PS	3.15	3.41	--	--
	ST	3.70	4.41	--	--		ST	2.36	3.04	--	--
	SA	<2.00	2.70	--	--		SA	<1.00	<1.00	--	--
3/7/76	TC	3.60	4.04	--	--	3/9/76	TC	4.36	5.11	--	--
Lake A	FC	1.48	1.95	--	--	Lake B	FC	2.78	3.91	--	--
	FS	2.04	2.34	--	--		FS	2.78	3.83	--	--
	PS	<1.00	1.70	--	--		PS	<1.00	1.95	--	--
	ST	2.32	3.28	--	--		ST	2.28	4.50	--	--
	SA	<1.00	<1.00	--	--		SA	<2.00	<2.00	--	--
3/7/76	TC	4.20	4.88	--	--	3/9/76	TC	3.63	4.43	--	--
P-10	FC	2.64	3.77	--	--	Lake A	FC	2.20	2.47	--	--
	FS	2.70	3.40	--	--		FS	2.28	2.86	--	--
	PS	<1.00	2.45	--	--		PS	<1.00	1.70	--	--
	ST	2.45	3.15	--	--		ST	2.70	3.28	--	--
	SA	<2.00	2.30	--	--		SA	<1.00	<1.00	--	--

TABLE 4. SUMMARY OF INDICATOR AND PATHOGEN BASE LEVELS, PEAK LEVELS AND TIMES DURING STORM (CONT'D.) EVENTS.

Station	Indicator	Log of No./100 ml Min.	Max.	Mean	Time @ Max., Hrs.
3/9/76	TC	4.08	4.96	--	--
P-30	FC	3.20	3.86	--	--
	FS	3.56	4.03	--	--
	PS	1.00	2.11	--	--
	ST	3.95	4.48	--	--
	SA	<2.00	<2.00	--	--
4/5/76	TC	3.72	4.26	--	--
P-10	FC	1.90	2.50	--	--
	FS	2.30	2.76	--	--
	PS	<2.00	2.30	--	--
	ST	1.48	2.28	--	--
	SA	<1.00	1.00	--	--
4/5/76	TC	3.00	5.77	--	--
P-30	FC	<2.00	4.00	--	--
	FS	<2.00	4.59	--	--
	PS	<2.00	3.00	--	--
	ST	2.00	4.59	--	--
	SA	<2.00	2.30	--	--
4/5/76	TC	4.81	6.51	--	--
Lake B	FC	2.90	3.78	--	--
	FS	2.49	3.11	--	--
	PS	<2.00	2.70	--	--
	ST	3.45	4.45	--	--
	SA	<2.00	2.00	--	--
4/5/76	TC	3.76	3.97	--	--
Lake A	FC	1.48	2.79	--	--
	FS	2.69	3.09	--	--
	PS	1.00	1.90	--	--
	ST	2.00	2.89	--	--
	SA	<1.00	<1.00	--	--

TABLE 5. SUMMARY OF PHYSICAL FACTOR PEAK VALUES AND TIMES DURING STORM EVENTS.

Station	Time to Peak, Hrs. (Max. Value) Q(cfs)	SS(mg/l)	T(J.T.U.)	Rain Amt., in.	No. of Samples
1/18/74					
P-30	19.5(1,250)	4.5(2,090)	4.5(500)	2.02	46
4/22/74					
P-30	8 (9.6)	10 (1,600)	11 (500)	0.45	49
10/28/74					
P-30	3.6(107)	7 (1,208)	8 (1,460)	3.46	58
12/5/74					
P-30	5.3(279)	2 (667)	1 (350)	1.59	17
P-10	3.6(195)	1.5(120)	1.5(70)	1.52	57
3/12/75					
P-30	20 (25)	-(222)	-(132)	0.75	5
3/12/75					
P-10	19.5(56.8)	17 (170)	17 (85)	0.69	32
Lake B	26 (11.7)	16 (5,358)	16 (2,000)	0.81	20
Lake A	21 (2.0)	-(164)	-(108)	0.81	27
P-30	20 (25)	-(222)	-(132)	0.75	5
3/4/75					
P-30	0 (4.9)	-(62)	-(45)	0.33	8
Lake B	1.5(0.3)	2 (326)	2 (490)	0.26	13
Lake A	-(0.0)	-(194)	-(125)	0.26	11
4/7/75					
P-30	40 (1,060)	13 (672)	20 (285)	2.43	26
P-10	32.5(1,225)	18 (226)	18 (100)	2.43	34
Lake B	14 (96)	20 (2,660)	13 (900)	3.97	38
Lake A	23.2(113)	26 (356)	26 (210)	3.97	38

TABLE 5. SUMMARY OF PHYSICAL FACTOR PEAK VALUES AND TIMES DURING STORM EVENTS. (CONT'D.)

Station	Time to Peak, Hrs. (Max. Value) Q(cfs)	SS(mg/l)	T(J.T.U.)	Rain Amt., in.	No. of Samples
9/5/75					
P-30	21(9.0)	21(158)	29(162)	0.35	4
P-10	-(0.3)	-(9)	-(4)	0.25	12
Lake B	None	30(2,766)	30(1,440)	1.11	8
Lake A	None	-(34)	-(24)	1.11	16
10/25/75					
P-30	17(56)	17(398)	17(265)	--	14
P-10	20(22)	2(42)	2(28)	--	30
Lake B	---	1(1,276)	1(680)	--	12
Lake A	15(15)	-(78)	-(28)	--	23

when too few samples were obtained to portray the complete storm, or the amount of flow was of such a small order of magnitude as to render additional data evaluation meaningless. That is also true for missing mean values in the data presented in Table 4. Those data substantiate the belief that a first flush effect occurs during storm events, regardless of the magnitude and duration of the hydrograph. In the majority of instances both indicator and pathogen populations peaked in concentration prior to or very near the point in time through the storm event at which the flow volume demonstrated peaking. That was also true for turbidity (T) and suspended solids (SS) concentrations. By visual inspection alone, there appeared to have been little correlation of the amount of rainfall and peak SS, T, or bacterial levels. Perhaps the soil conditions prior to each storm event influenced the runoff quality.

The storm event of 4/7/75 was chosen as that which represented the most typical event which was monitored. Figures 8 through 15 present some of the microbiological data derived from stations P-10 and P-30 during the storm. Total coliform concentrations demonstrated a less clearly defined curvature when graphed than did the FC and FS concentrations. All three of those groups peaked well in advance of the hydrograph peak. FC and FS densities peaked earlier at station P-30 than at the upstream station (P-10) (Figures 8-11). A similar trend can be observed in the data presented in Figures 12 and 13 for staphylococci. Data for the other pathogens (PS and SA) are not included in graphical format due to their highly erratic concentrations versus time through the storm. Attention should be given the FC/FS values for both stations plotted in Figures 14 and 15. Those occurring through the storm at P-10 were obviously extremely erratic whereas virtually all of those at station P-30 held near or below 1.0 throughout the storm. Data such as these obviate the need for a statistical approach to analysis rather than simple examination.

TEXAS WATER QUALITY STANDARDS AND WOODLANDS STORMWATER BACTERIA CONTENT

Conditions existing at P-10, P-30 Lakes A and B during low flow periods with regard to FC contact and noncontact recreation standards have been discussed earlier in this report. The Texas standards apply even more directly to stormwaters because in virtually all sequences more than five samples were obtained within the thirty day prescribed time period. Recall the standard for contact recreation; FC not to exceed 200/100 ml (log = 2.3) as a geometric mean and in less than 10% of the samples they should not exceed 400/100 ml. For noncontact recreation the figures are one

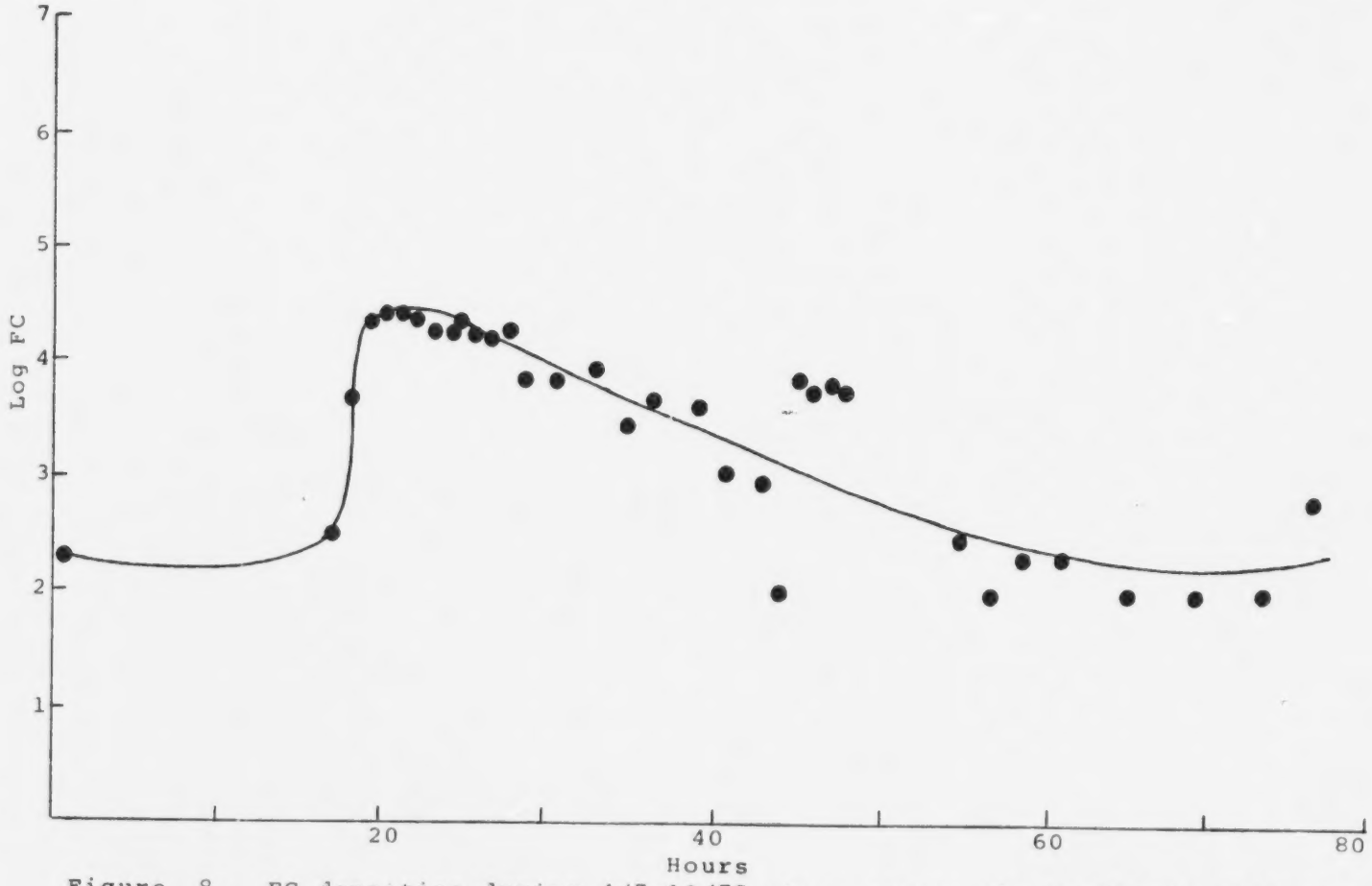


Figure 8. FC densities during 4/7-10/75 storm event; the Woodlands station P-10.

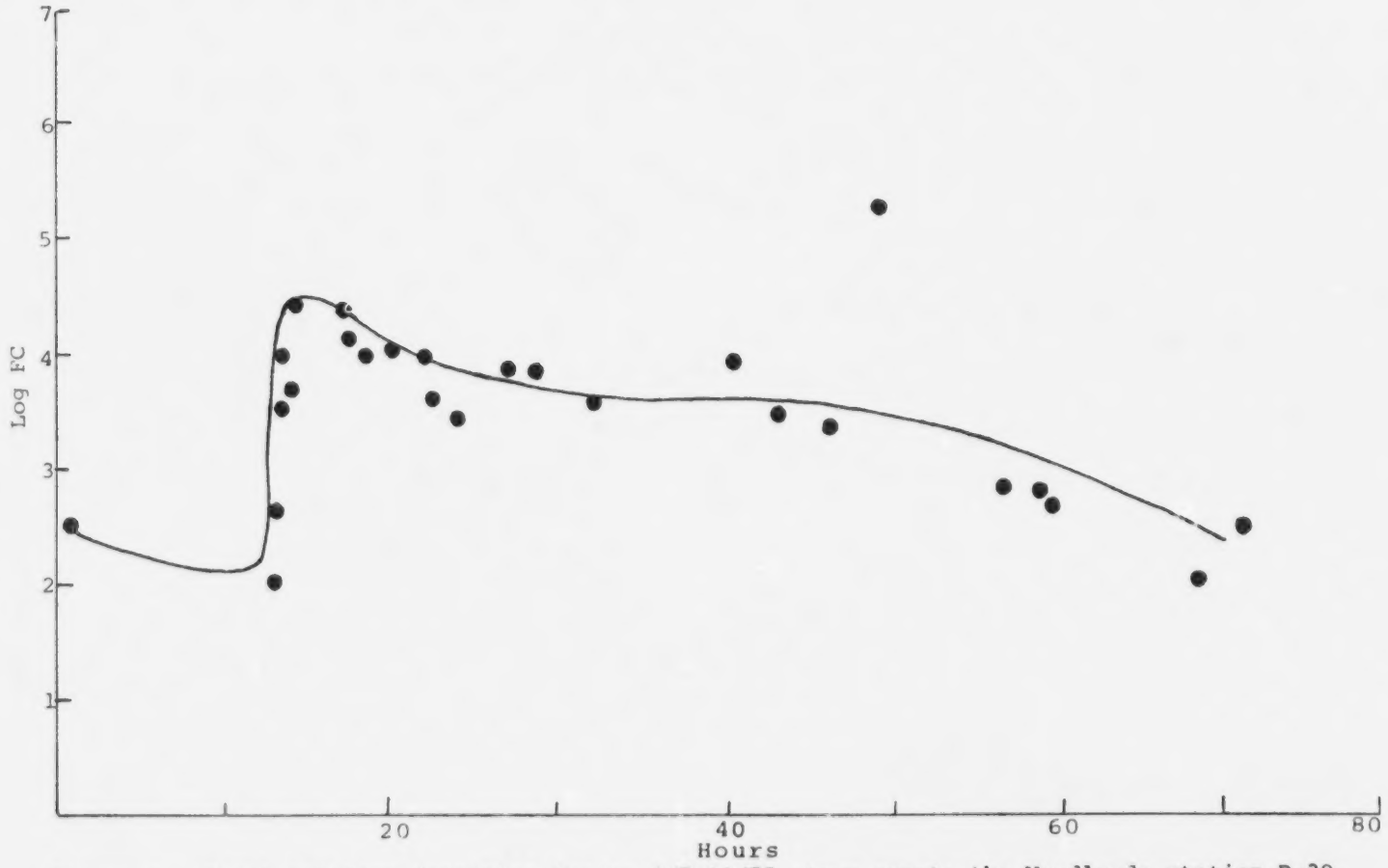


Figure 9. Fecal coliform densities during 4/7-10/75 storm event; the Woodlands station P-30.

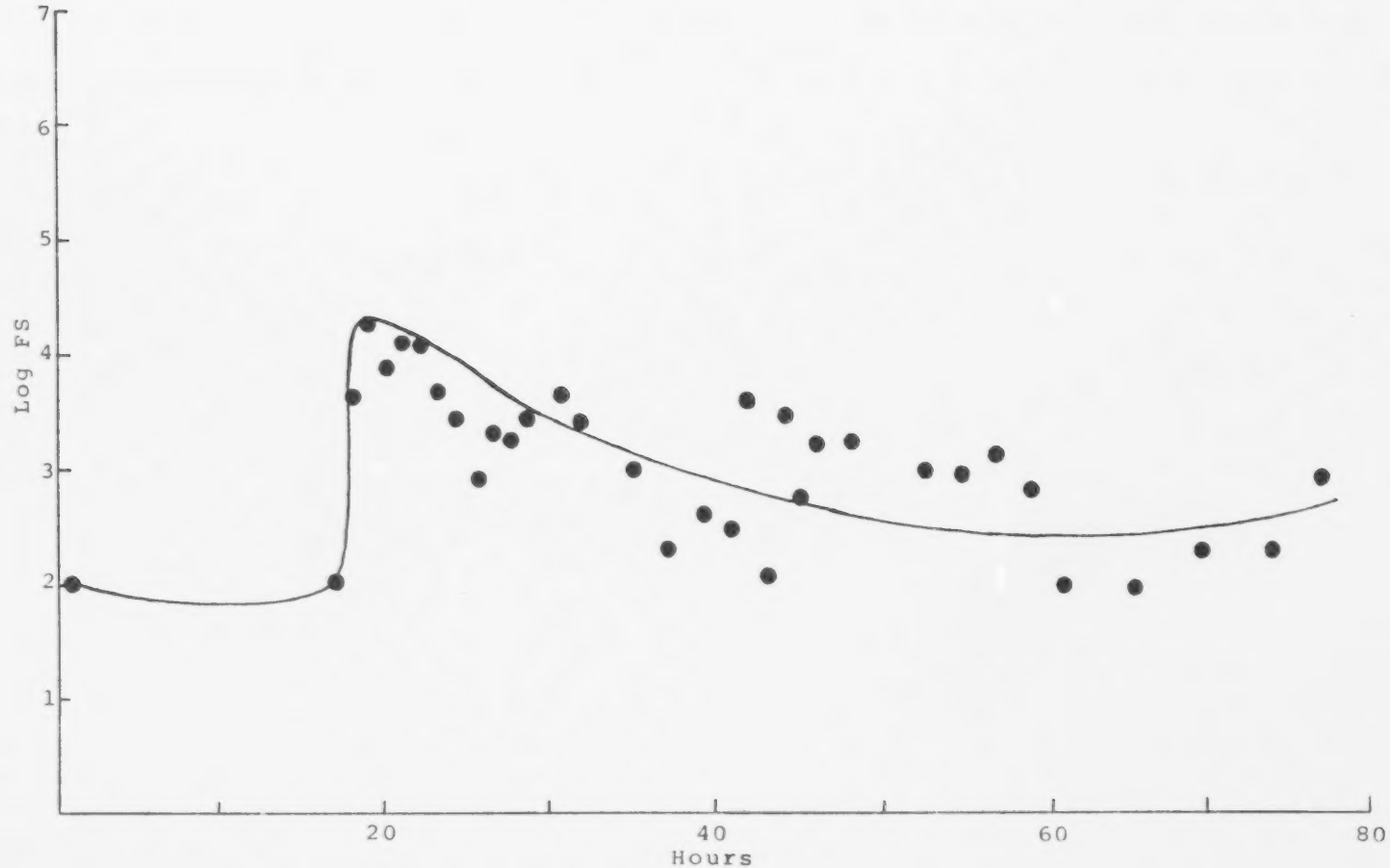


Figure 10. FS densities during 4/7-10/75 storm event; the Woodlands station P-10.

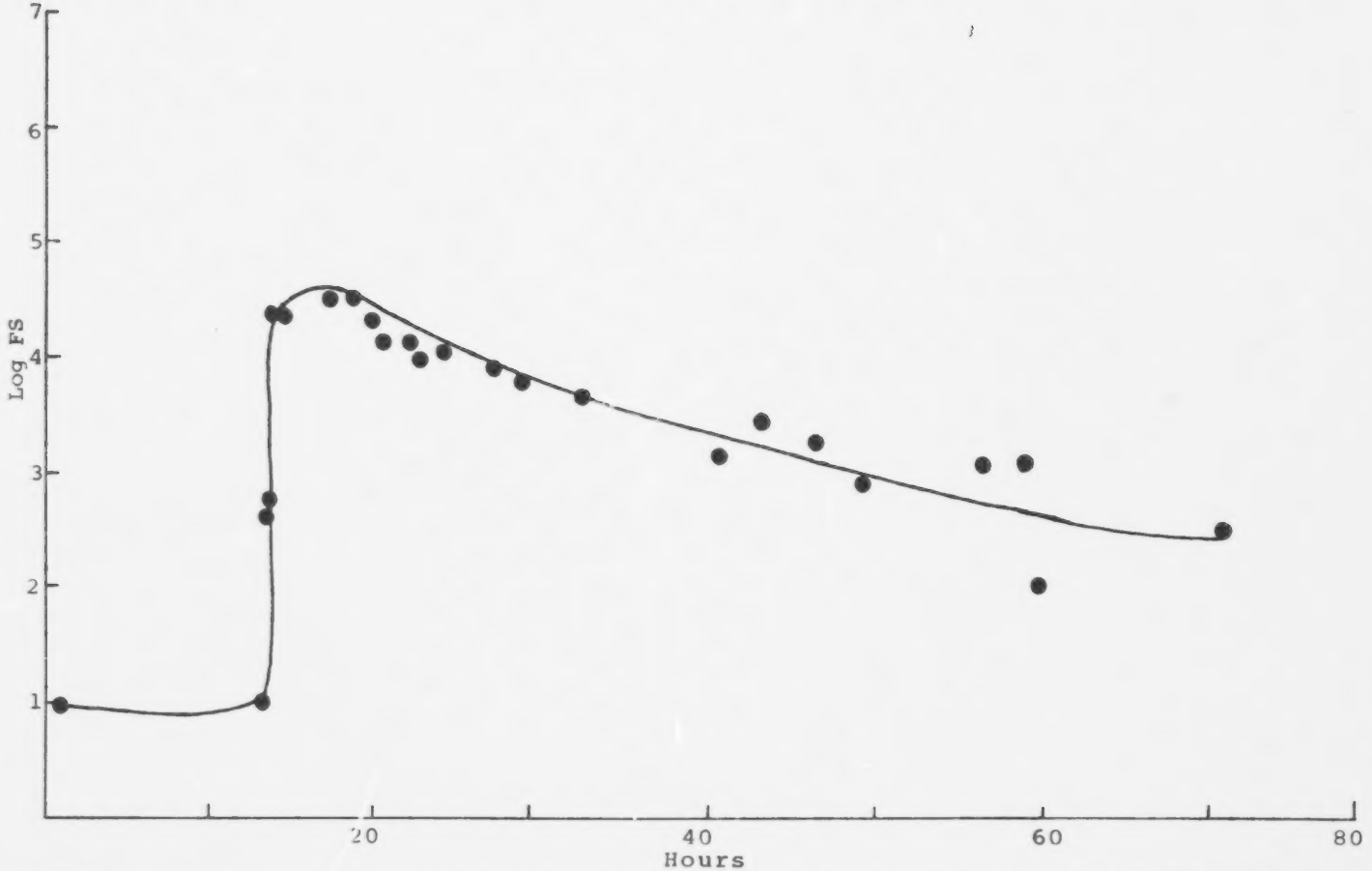


Figure 11. Fecal streptococci densities during 4/7-10/75 storm event; the Woodlands station P-30.

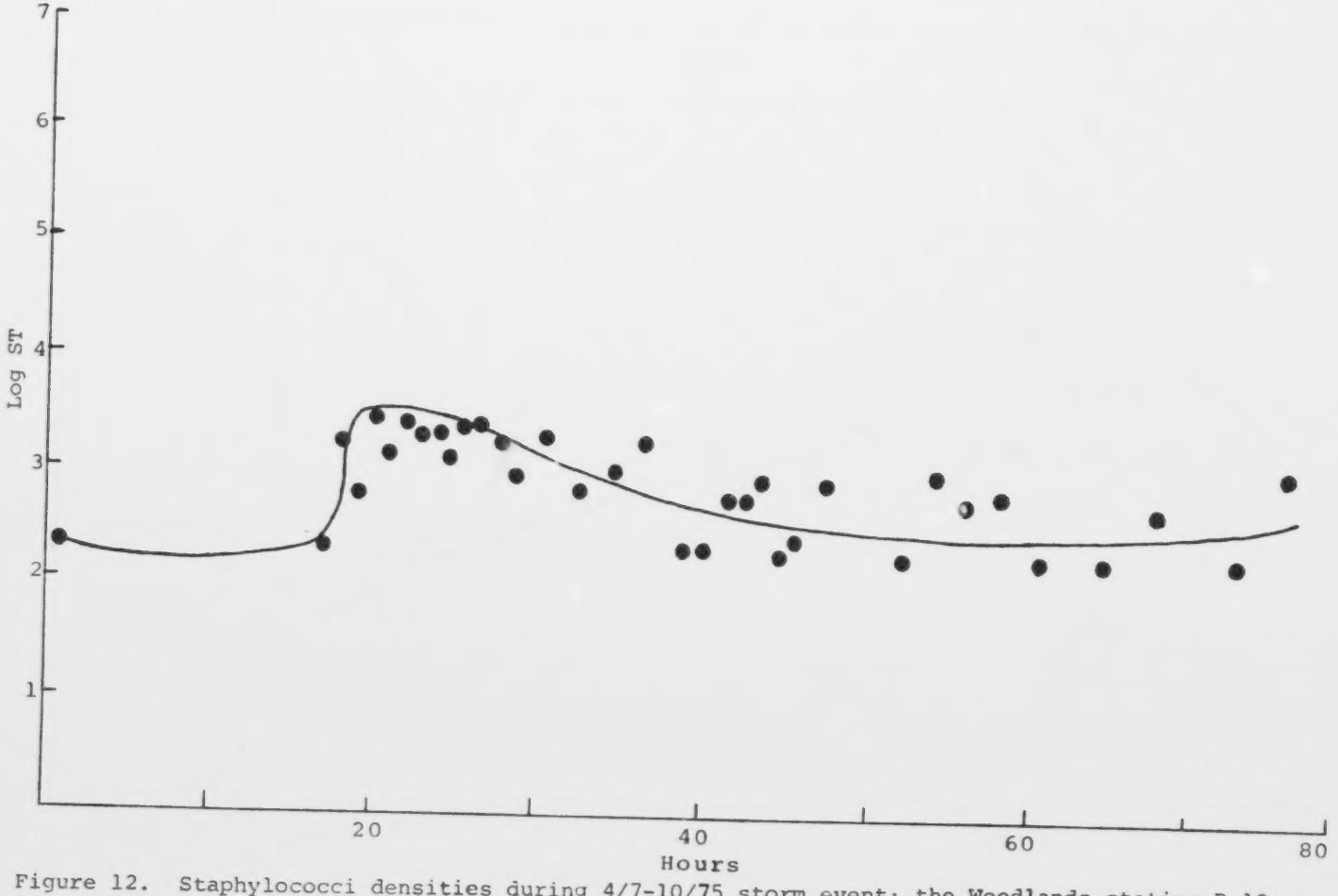


Figure 12. Staphylococci densities during 4/7-10/75 storm event; the Woodlands station P-10.

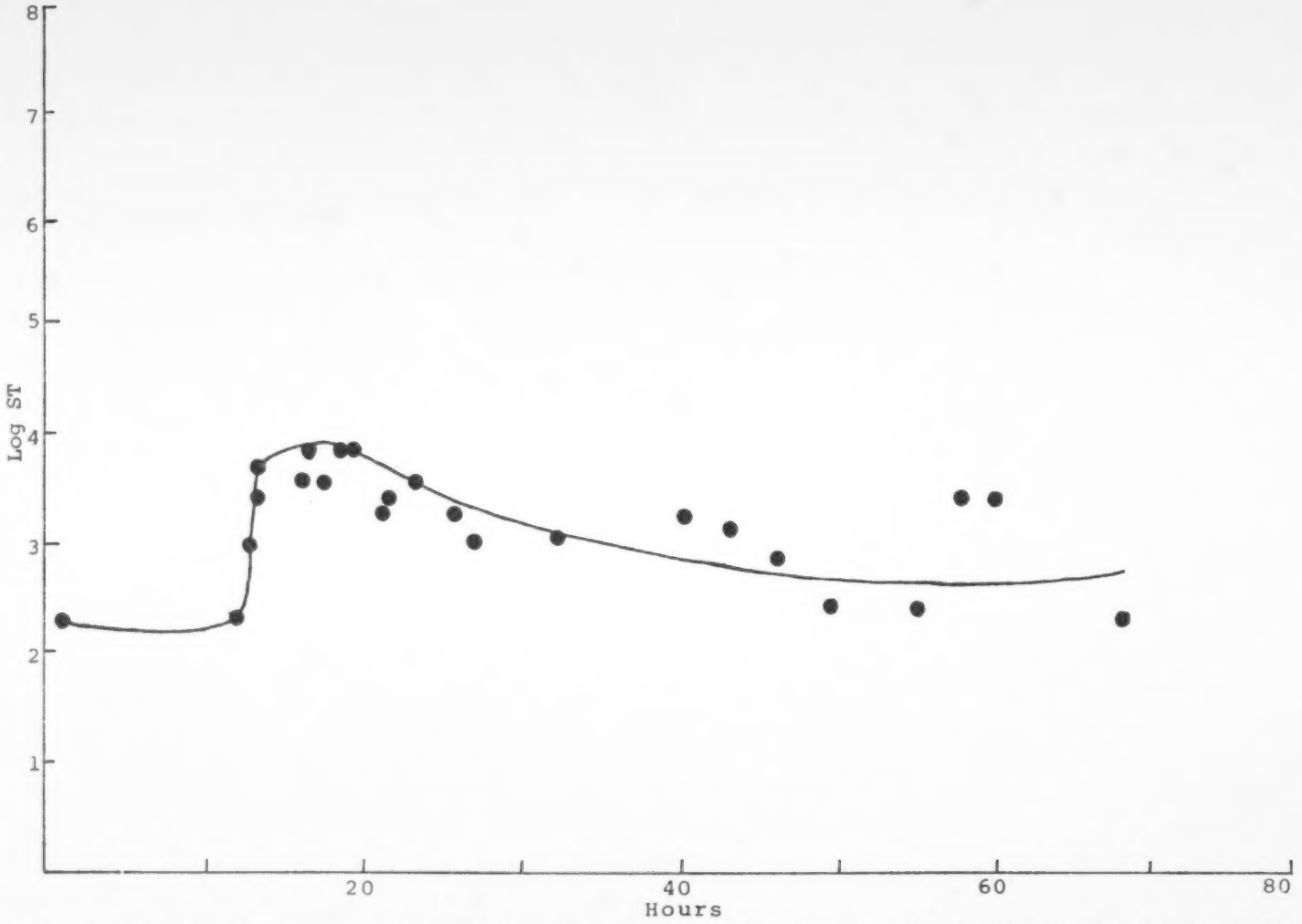


Figure 13. Staphylococci relationships during 4/7-10/75 storm event; the Woodlands station P-30.

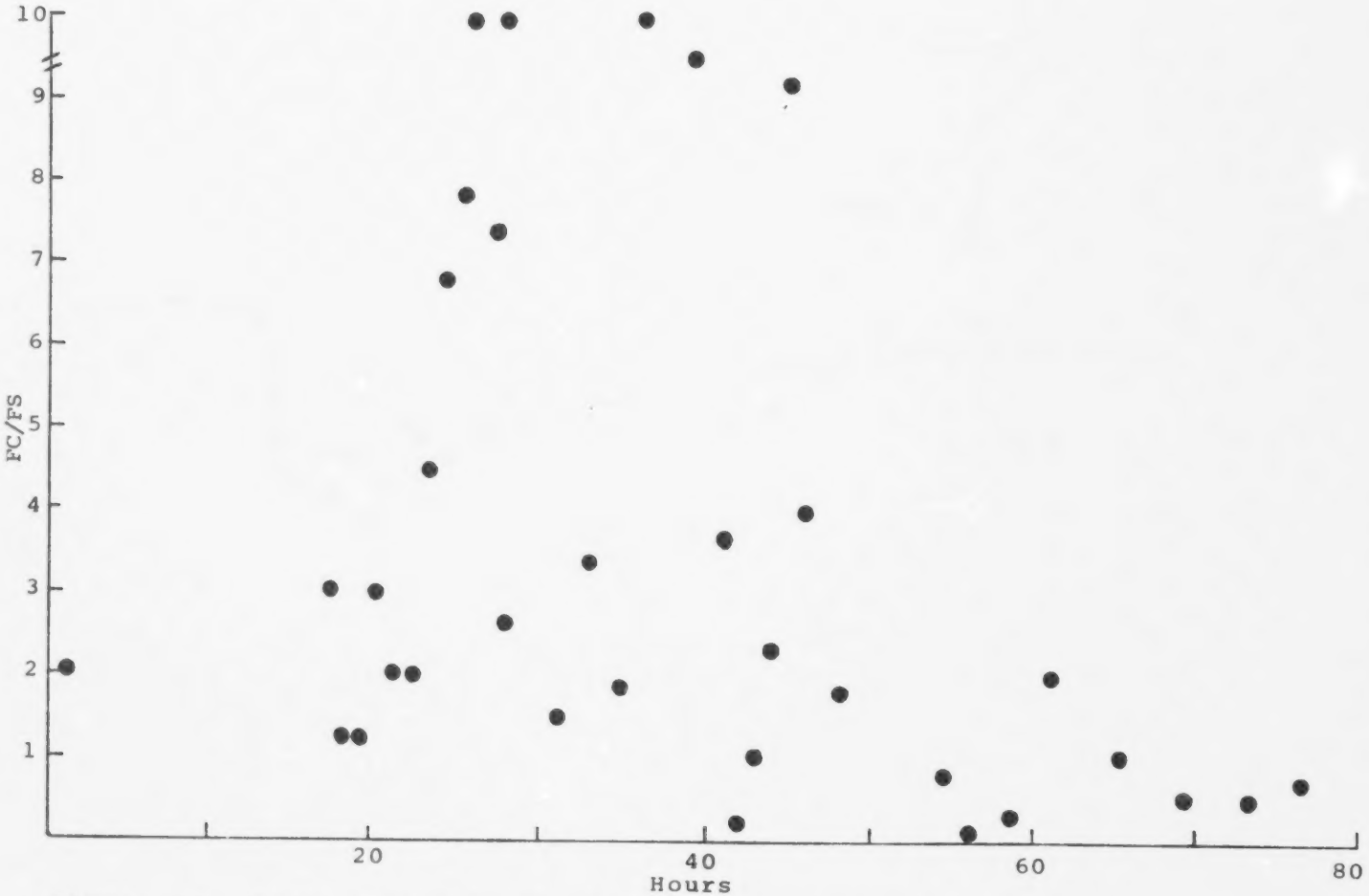


Figure 14. FC/FS ratios during 4/7-10/75 storm event; the Woodlands station P-10.

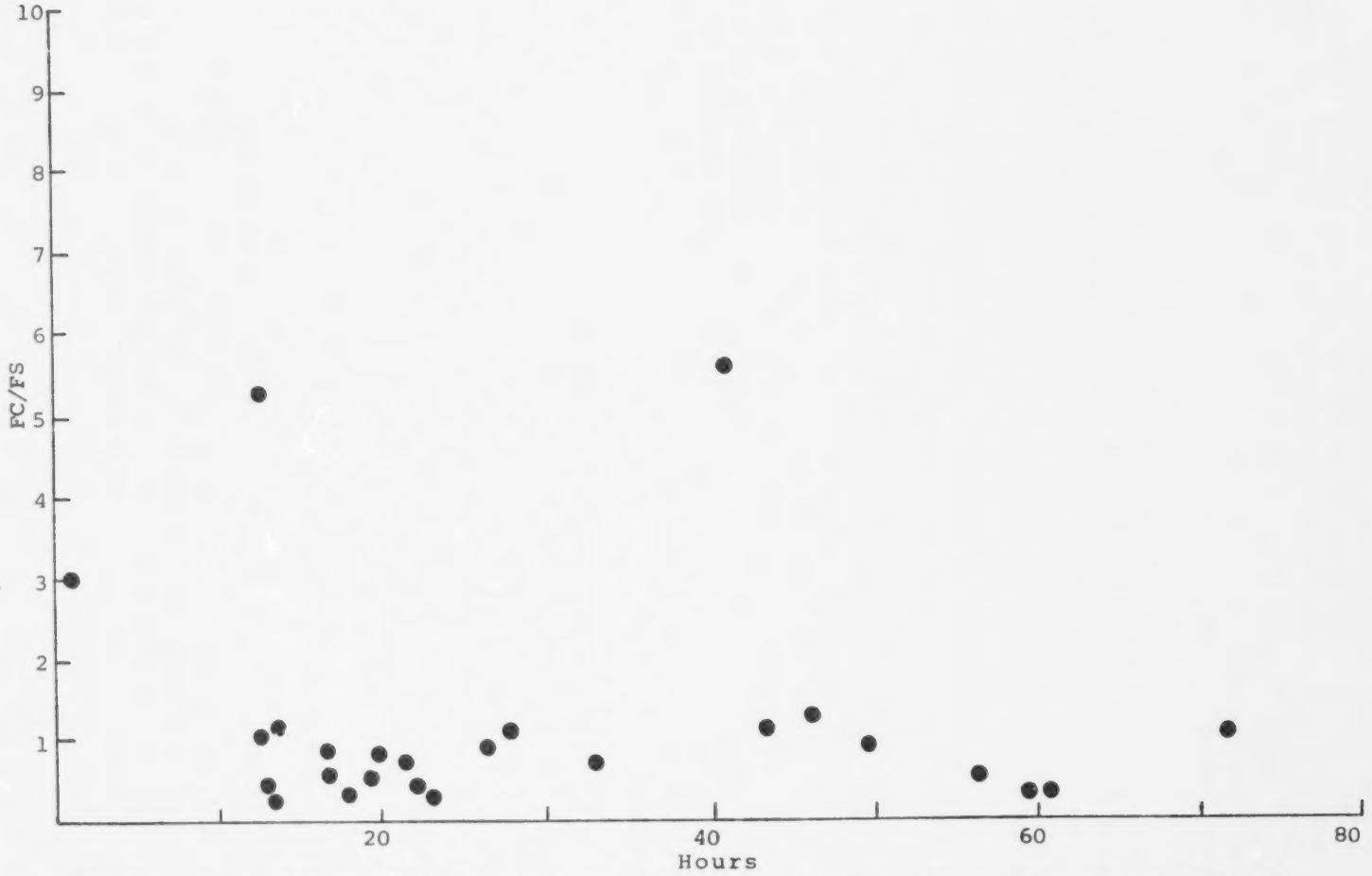


Figure 15. FC/FS relationships during 4/7-10/75 storm event; the Woodlands station P-30.

order of magnitude higher, i.e., 2,000/100 ml and 4,000/100 ml in less than 10% of the samples taken in a 30-day period. Comparisons of storm event data can be easily accomplished with the idea of estimating the sedimentation effect of the lakes (referred to earlier) and distance downstream from P-10 to P-30. Table 6 summarizes the data for the storms and indicates whether the contact and noncontact standards were exceeded based on geometric mean FC values for each storm indicated.

The only source of the four listed in Table 6 which did not exceed contact recreation FC values was the Lake A effluent during two of five events. All others exceeded that standard. Thirteen of 24 storms, considering all stations, exceeded the noncontact recreation standard of 2,000/100 ml.

MATHEMATICAL APPROACHES TO DETERMINATION OF BACTERIOLOGICAL WATER QUALITY

The first phase of data analysis by computer analysis included data obtained through March, 1975. Multiple regression analyses were conducted using several sets of low flow and storm event data. Those analyses employed a step-wise regression technique which determined the relationship between the bacteria count, set as the dependent variable, and other bacteria counts and the other water quality factors set as independent variables. Data which were used in those analyses were from the following low flow monitoring and selected storm events:

Low Flow - Inclusive of Stations B-09, P-09, P-10, P-20, P-25, P-30, and P-40 for 9/7/74, 2/7/75, 2/18/75, and the diurnal low flow of September 21-22, 1975 at Stations P-10 and P-30.

Storm Events - 10/28-31/74 (P-30), 12/5-9/74 (P-10 and P-30), 3/4/75 (P-30), and 3/12-14/75 (P-10 and P-30).

231 data were employed for those analyses.

The cross correlation matrix developed from using bacterial counts in their usual numerical form is presented in the following table. Those data show the highest R^2 values to have been between fecal streptococci with discharge ($R^2 = 0.75$) and suspended solids with discharge ($R^2 = 0.71$): (T = turbidity, J.T.U.; Q = discharge, cfs; SS = suspended solids, mg/l).

TABLE 6. FECAL COLIFORM GEOMETRIC MEANS DURING STORM EVENTS.

Storm:	Geo. Mean	Geo. Mean Exceeds Std. For: Contact Rec.	Noncontact Rec.	Supp. Data
		Station P-10		
12/5/74	3.20	Yes	No	15/58>4,000
3/14/75	2.93	Yes	No	---
4/8/75	3.36	Yes	Yes	---
9/5/75	2.41	Yes	No	---
10/25/75	3.48	Yes	Yes	---
		Station P-30		
1/18/74	3.63	Yes	Yes	---
4/22/74	3.89	Yes	Yes	---
10/28/74	3.63	Yes	Yes	---
12/5/74	3.86	Yes	Yes	---
3/4/75	3.00	Yes	No	---
3/13/75	2.41	Yes	No	1/5>4,000
4/8/75	3.38	Yes	Yes	---
9/5/75	3.39	Yes	Yes	---
10/25/75	4.17	Yes	Yes	---
		Lake B		
3/4/75	3.38	Yes	Yes	---
3/12/75	3.12	Yes	No	1/21>4,000
4/8/75	3.37	Yes	Yes	---
9/5/75	3.90	Yes	Yes	---
10/25/75	4.22	Yes	Yes	---
		Lake A		
3/4/75	0.85	No	No	---
3/12/75	1.44	No	No	---
4/8/75	3.03	Yes	No	5/39≥4,000
9/5/75	2.36	Yes	No	---
10/25/75	2.41	Yes	No	---

ST	.33471							
SA	.18274	.37348						
TC	.43297	.46562	.20925					
FC	.34707	.30922	.17502	.37188				
FS	.63224	.68690	.24429	.56734	.54247			
SS	.42237	.44566	.10987	.30088	.49152	.57878		
Q	.37058	.84900	.38854	.43463	.44541	.75013	.70998	
T	.15363	.52922	.46259	.27847	.29076	.35788	.03861	.55439
	PS	ST	SA	TC	FC	FS	SS	Q

Plotted relationships of bacteria counts and SS, T, and Q were, for the most part, nonlinear. When transformed to semilog plots, the relationships were much more useful in data manipulation. Log base-10 values for bacterial densities were then rerun using the same computer program for multiple regression analysis. SS, Q, and T values were not entered as log values. The results are presented in the following summary matrix tabular format.

ST	.48310							
SA	.45079	.32302						
TC	.33548	.53282	.27482					
FC	.48222	.59134	.29133	.47659				
FS	.53829	.76638	.40474	.55472	.81061			
SS	.50524	.59214	.32590	.34821	.50260	.61729		
Q	.52644	.73667	.40444	.41138	.46280	.70600	.70998	
T	.38069	.40761	.36398	.32760	.43997	.44268	.03861	.55439
	PS	ST	SA	TC	FC	FS	SS	Q

The highest R^2 values shown in those results were FS and FC ($R^2 = 0.81$) and ST and FS ($R^2 = 0.76$). Finalized models for the period of the investigation for which data were analyzed through May, 1975 are presented in Table 7. In reviewing those models, several important factors become evident. For example the FS was used as an independent variable in three of the models and was, in fact, the independent variable entered in the step-wise regression. That proved it to have been the variable which explained the most variance in the dependent variable when used above. Additionally, in the FC and FS models, their coefficients were nearly equal, i.e., .719 vs .720. Their densities therefore were influenced by runoff factors (discharge, turbidity, and solids) but with opposing effects. FC increased with increases in turbidity and solids and FS decreased. On the other hand FS increased with increases in discharge and FC counts decreased. Those models (Table 7) strongly suggest the FS group to have been the most useful indicator group. Since the FC were not used in the models for pathogenic bacteria, they cannot be considered to have been adequate indicators of fecal pollution in the test site. It is important to note that due to the high numbers of data used for those analyses, all R^2 values presented in Table 7 are statistically significant.

TABLE 7. SUMMARY TABLE OF MODELING EQUATIONS

		R^2
Pseudomonas aeruginosa	PS = .195 FS - 13.608 Q + .983 SS + 6.645 T - 3.669	.47
Pseudomonas aeruginosa(log)	PS = .206 FS + .002 SS + .002 T + 1.063	.40
Staphylococcus aureus	ST = 153.276 Q - 59.167 SS + .002 TC - 23.122 T - 1,344.787	.79
Staphylococcus aureus(log)	ST = .363 FS + .002 Q + .183 TC + .439	.68
Salmonella	SA = .560 T + .826 Q + 79.476	.24
Salmonella (log)	SA = .240 PS + .002 T + .001 SS + .594	.27
Total Coliforms	TC = 39.122 FS + 543,719.80	.32
Total Coliforms(log)	TC = .408 FS + 4.102	.31
Fecal Coliforms	FC = .141 FS + 17.731 SS + 16.271 T - 15.487 Q + .494	.42
Fecal Coliforms(log)	FC = .719 FS - .002 Q + .003 T + .002 SS + .612	.77
Fecal Streptococci	FS = 58.010 Q + .003 TC + .704 FC - 19.975 T - 2,798.547	.67
Fecal Streptococci(log)	FS = .720 FC + .002 Q + .151 TC - .001 T - .001 SS - .170	.82

An additional analysis of variance was conducted on storm event and low flow data for 12/5-9/74, 3/12-14/75, 4/7-10/75, 9/5-6/75, 10/25-27/75, the diurnal study of 9/21/74, and low flow data. The procedure assumed sampling of normally distributed populations. Since P-30 and P-10 represented major categories, separate frequency diagrams were constructed. The distributions of raw bacteriological data were markedly skewed. The log transformed data eliminated most of that skewness, however the diagrams appeared to represent the two overlapping populations of low flow and storm data. Therefore, storm and low flow frequency diagrams were constructed separately for the transformed data. This effectively reduced skewness and kurtosis on all variables.

In all the bacteriological data presented herein the geometric mean closely approximates the median value, proving a normal distribution occurred in the populations, thus validating the applied statistics. Differences between, for example, upstream and downstream stations can be cited as multiplicative differentials. This is important in denoting urbanization effects and land use effects on runoff water quality.

Separate Applications of Multiple Regression Analyses

Analyses similar to those described for the earlier work were applied to all data from January, 1974 through June, 1975, plus a comparison of low flow and storm data was indicated. Regression analyses were conducted with computer control cards similar to those used in the earlier study except that an option was used to affect paired deletion of cases which contained missing-data values. Seventy-two regression equations were generated using log-transformed data. The usage comparisons were as follows:

Dependent Variable	Independent Variable
Log TC	Q, SS, T, log FC, log FS
Log FC	Q, SS, T, log TC, log FS
Log FS	Q, SS, T, log TC, log FC
Log PS	Q, SS, T, log TC, log FC, log FS
Log ST	Q, SS, T, log TC, log FC, log FS, log PS
Log SA	Q, SS, T, log TC, log FC, log FS, log PS

Independent variables were entered into the regression equations in a stepwise fashion by virtue of their partial correlation to the dependent variable; the highest correlated independent variable having been entered first, followed by

the next independent variable that best improved the R^2. The first independent variable entered into the equations always indicated the highest percentage of the explained variance of the entire equation; the second variable entered would improve the R^2 by a lesser amount. The maximum change in R^2 for the second independent variable entered in those equations was 0.21. Most of the changes were considerably lower. A comprehensive listing of all the regression equations would be pointless. The variables entered into the equation, their order, and the percent variance in the dependent variable explained by the equations were altered with different analytical treatments (sequences) of the data. Some deviations were observed in the correlation matrices. The examination of the results which follows explains some of the anomalies mentioned above. The data were subdivided into the following 11 individual sequences.

Sequence 1: All storm event and low flow data through June, 1975 (n = 669)--

Log FS produced the highest correlations, and was apparently the best predictor of the other bacterial populations which were examined. For all the data, Log FS gave the highest correlations with Log TC (R^2 = .31), Log FC (R^2 = .45), and Log ST (R^2 = .39). The FC/FS ratio yielded low correlations many of which were insignificant at the 5% level. SS and T yielded correlations greater than R^2 = .75.

Sequence 2: All storm data through June, 1975 (n = 486)--

The storm event correlations tended to be higher and more significant than the low flow data and all the combined data. With the storm event data, Log ST gave the highest correlations and Log FS the second highest. Their R^2 ranges were as follows: Log ST = .06 - .46; Log FS = .17 - .46. The correlations involving the FC/FS ratios were low and only one, FC/FS with Log SA (R^2 = .02) was significant at the 5% level.

Sequence 3: All low flow data through June, 1975 (n = 181)--

The low flow data exhibited 22 of 37 correlations that were insignificant at the 5% level. The correlations involving FC/FS ratios were low for all bacterial densities and most were insignificant at the 5% level.

Sequence 4: Complete storm data--

Regressions were conducted with storm event data which contained no missing values to determine if inclusion of

cases with missing values affected the correlation coefficients. This necessarily decreased the number of cases and the degrees of freedom. The resulting correlations varied. The correlations of FC/FS ratios with other bacterial densities were not significant at the 5% level.

Sequence 5: Lake B storm data through June, 1975 (n = 74)--

For Lake B storm event data, the best predictor was Log FS. It gave the highest correlations for Log ST (R^2 = .49). All correlations involving Log SA were not significant at the 5% level. The FC/FS ratios yielded low and/or negative correlations with other variables.

Sequence 6: Lake A storm data through June, 1975 (n = 79)--

Lake A storm event correlations were difficult to interpret. Log PS gave the highest correlations with other bacterial densities but all were below R^2 = .50. Log FS ranked third after Log FC. significant correlation involving Log SA was with Log PS which was -.39 (R^2 = .16). The FC/FS ratios yielded some significant correlations at the 5% level.

Sequence 7: All P-30 storm data through June, 1975 (n = 208)--

This and sequence 10, below, yielded R^2 values of greater than 0.75. The model which did that was

$$\text{Log ST} = .000668T + .779 \text{ Log FS} + .000625 \text{ SS} - .489 \text{ Log FC} + .167 \text{ Log TC} + 1.051$$

and had an R^2 = .79.

Sequence 8: P-10 storm data through June, 1975 (n = 125)--

For station P-10 storm events, the correlations involving FC/FS ratios were not significant at the 5% level for all bacterial densities except Log SA with R^2 = .20. Log FS yielded high correlations (R^2 = .28) for Log TC, (R^2 = .63) for Log FC, and (R^2 = .50) for Log ST. SS and T values yielded R^2 values greater than .75.

Sequence 9: Storm event of 12/5-9/74 (stations P-10 and P-30) (n = 74); Sequence 10: Storm event of 3/12-14/75 (station P-10, P-30, Lakes A&B)(n = 97); and Sequence 11: Storm event of 4/7-10/75 (station P-10, P-30, Lakes A&B) (n = 14)--

For each storm event tested, the Log FS values appeared to have been the best predictors of bacterial densities measured. FC/FS ratios yielded low and/or not significant correlations at the 5% level for most variables.

The three storm events were chosen for analysis because they were thought to represent the most typical hydrographs. Q, SS, T, Log TC, Log FC and Log FS were always specified as independent variables. The following table reinforces the earlier conclusion that FS were the best predictors for Woodlands bacterial water quality data.

A	B	C	D
Q	1	7	66
SS	2	2	66
T	5	11	66
Log TC	10	5	58
Log FC	17	3	58
Log FS	28	4	58

A = Independent variable.
B = No. of times the independent variable was the first variable entered into an equation.
C = No. of times the independent variable was the second variable entered into an euqation.
D = No. of equations being examined.

The models developed in sequence 10, and summarized below, yielded the highest R^2 values.

$$\text{Log PS} = .000862T + .665 \text{ Log TC} - .0233Q - 1.757 \quad (R^2 = .85)$$

$$\text{Log ST} = .259 \text{ Log TC} + .000612T + .968 \text{ Log PS} + .0278Q - .209 \text{ Log FC} - .589 \quad (R^2 = .90)$$

SS and T values in sequences 10 and 11 also yielded R^2 values greater than .75.

In summary, the FC/FS ratios were of little use in predicting the presence of pathogens, based on correlations derived for the 5% level. Log FS appeared to have been the most promising predictor, yielding higher correlations for most bacterial densities measured and most data treatments. However, Log TC gave some higher correlations for stations P-10 and P-30 storm event data. P-10 and P-30 data represented approximately 50% of all the data. Salmonella sp. densities were difficult to predict. Some correlations were encountered but they were not consistent between the data sequences.

Inspection of all the data developed through June, 1975 revealed that, 1) six samples did not contain Fecal Coliforms when Salmonella sp. were detected; 2) seven samples did not contain Fecal Streptococci when Salmonella sp. were detected; 3) twenty-nine samples did not contain Pseudomonas aeruginosa

when Salmonella sp. were detected; and 4) three samples did not contain Staphylococcus aureus when Salmonella sp. were detected. However, no Salmonella sp. were detected when the Total Coliform densities were below 4,500/100 ml.

FC/FS RATIOS AND LAND USE

An important comparison employed in examining data is the relationship between FC and FS concentrations. A FC/FS ratio 4 suggests the presence of human wastes. Between 0.7 and 3.9, the FC/FS ratio may suggest human wastes mixed with other source materials. If values fall at or below 0.6, a predominance of livestock or other warm-blooded animal waste is suggested. Absolute conclusions derived from FC/FS values require a knowledge of sample storage history, point source FC/FS values, and the length of time the organisms were in the water prior to sampling.

Changes in natural forest cover to either clear cut areas for cultivation or for construction projects have been shown to result in measurable changes in water quality and hydrological factors (40). Leopold (39) cited distinctly measurable changes in lag times to peaking with urbanization. Claudon (38) stated that construction sites regularly contribute Vibrio cholerae, Salmonella typhi, Salmonella paratyphi, and Shigella dysenteriae to runoff volumes and that agricultural and urban runoff regularly contributes to Salmonella sp. in recreational waters. Geldreich, et al. (41) found the greatest median value for FS to have been 790,000/100 ml and occurred in winter. Tafuri (42) reported FC levels of 23,000/100 ml from a 1.67 sq. mi. (4.32 sq. Km) drainage area. Snowmelt and related agricultural runoff in far northern climes in the continental U.S. have been shown to contribute high densities of indicator bacteria and pathogens to runoff (43, 44). However, many urban area responses exceed rural agricultural runoff pollutant loadings (45). To identify a universal relationship for anticipated indicator or pathogen content in rural stormwater runoff would indeed constitute an exercise in futility. Each site must be examined and appraised on its own merit. Correlation efforts between runoff volumes and other water quality parameters generally result in meaningfully high values. But biological systems are a different matter entirely. This is further emphasized by the research conducted earlier by Winslow and Epsey (48). They developed good correlations in all analyzed factors against runoff volume except the indicator bacteria. Yet some predictive values for bacteria are possible on a site by site basis (46, 47). Physical factors such as suspended solids yield highest correlation values.

FC/FS ratios in water or wastewater of one, or less, point toward nonhuman pollution sources. Woodlands and Westbury sites demonstrated similar ratios for stormwater runoff and statistically related differences were not observed in three other areas considered herein. Those areas and/or stations were Westbury, Lakes A and B, P-10, and P-30. The FC/FS ratios appeared to be relatively constant regardless of sample site. This can easily be observed in the plotted data presented in Figure 16. That scalar approach to analysis shows two important factors. During storm events, the densities increased significantly but ratios remained relatively constant. The data points in Figure 16 represent mean FC and mean FS values. Increases occurred in FC and FS values with increased urbanization; Westbury being the site which was completely developed and P-10 and (to some extent) P-30 as rural areas. For further confirmation of these results, analysis of covariance was used to test the equivalence of least square regression lines for each of the five land use sites. The results of those analyses are presented in Figure 17 and Table 8. The lines representing P-10, P-30 and Lake B (influent) were analyzed simultaneously. Westbury and Lake A effluent data were analyzed separately due to their marked differences. FC and FS distributions were not constant for different land uses. Figure 17 shows the slopes decreasing with increases in urbanization and elevations increasing with increased urbanization, except for Lake A, where settling effects in the lakes resulted in decreased densities in Lake A outfall. Differences between densities of FC in incoming waters (Lake B) and Lake A effluent usually were at least one order of magnitude. FS densities decreased to a lesser extent. Increased FC densities with increased urbanization is more than strongly suggested.

The least Significant Difference (LSD) statistical analysis was applied to FC/FS ratios from all stations which were analyzed during this investigation. The following sequence resulted from that analysis:

Location	FC/FS (Geo. Mean)
Soil samples	0.16
Storms, Lake A	0.17
Storms, Lake B	0.53
Low Flow, Lake A	0.58
Chlorinated 2° Sewage	0.73
Low Flow, P-10	0.92
Storms, P-30	0.97
Low Flow, Lake B	0.99
Low Flow, P-30	1.26
Storms, Westbury	1.47
Low Flow Woodlands	1.68
Storms, P-10	2.11
Raw Sewage	2.42
2° Treated Sewage	13.30

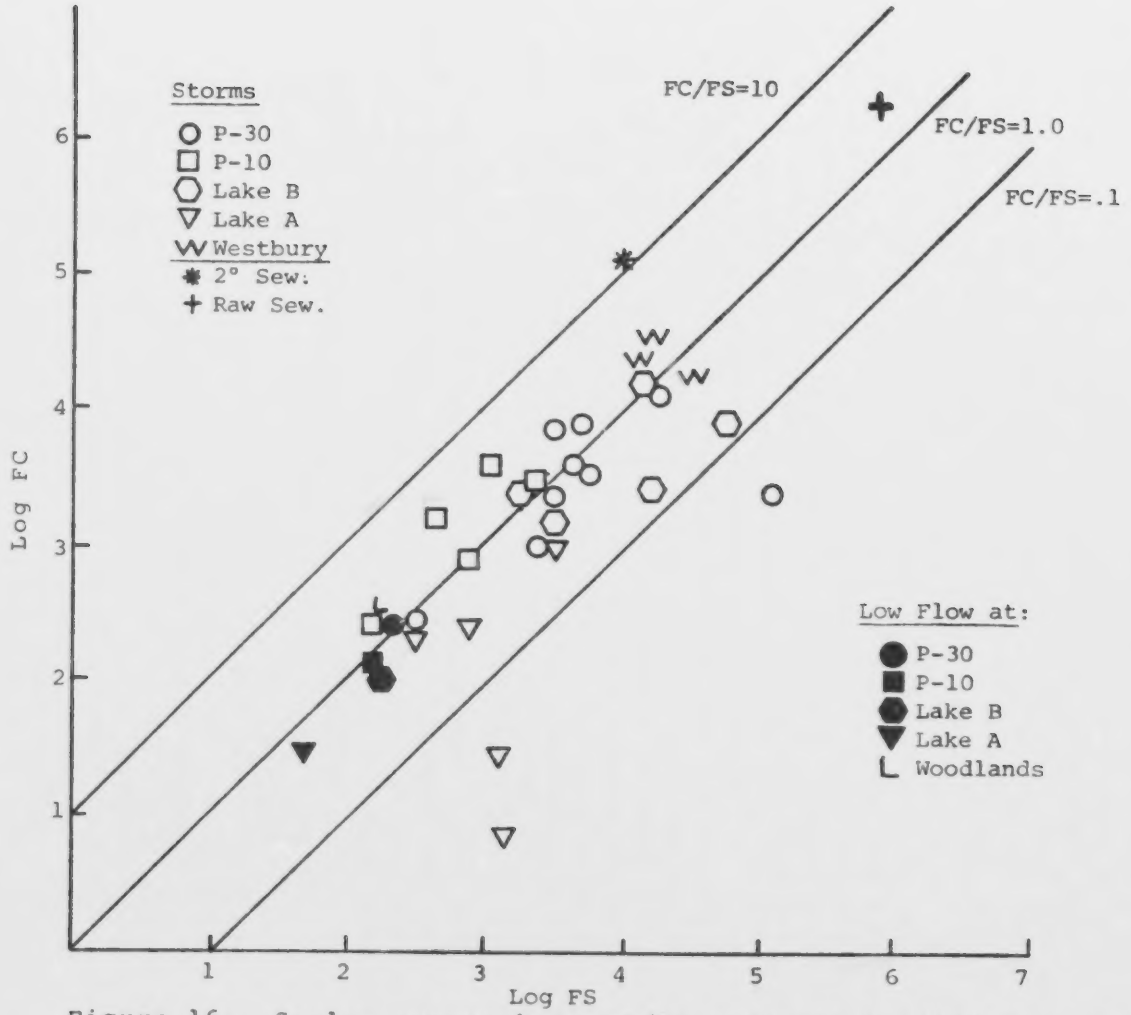


Figure 16. Scalar approach to FC/FS patterns in different land use areas.

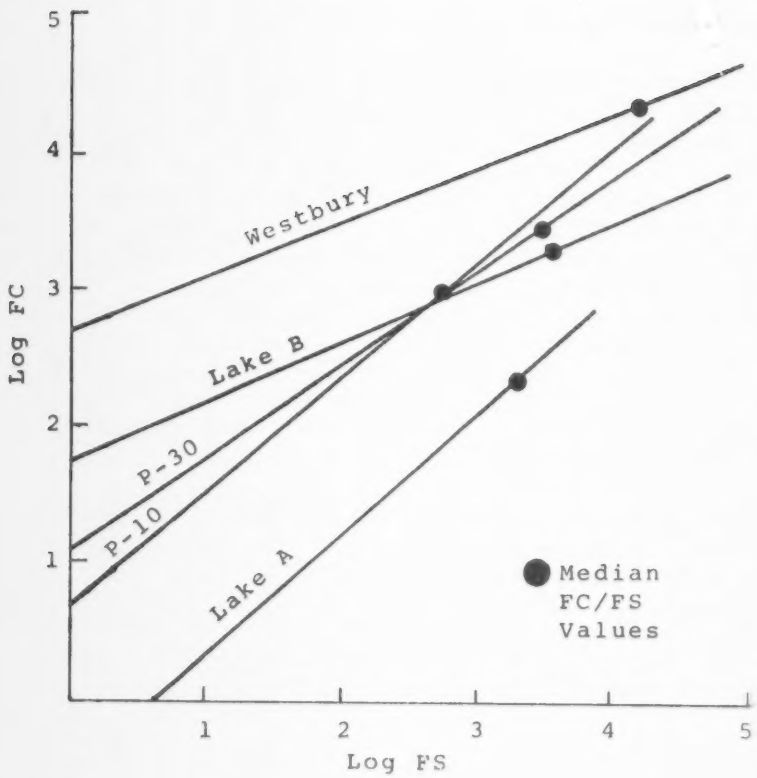


Figure 17. Fecal streptococcus vs. fecal coliform regression lines for five land use areas.

TABLE 8. MEANS, SLOPES, ELEVATIONS, AND CORRELATION COEFFICIENTS FOR FS ON FC REGRESSION LINES FOR LAND USE AREAS SHOWN IN FIGURE 17.

	r	r^2	b	a	n	Log $\overline{FS}$	Log $\overline{FC}$
Westbury	.56	.32	.40	2.76	28	4.22	4.39
Lake B	.54	.30	.48	1.75	89	3.56	3.31
P-30	.81	.66	.68	1.10	264	3.47	3.47
P-10	.77	.59	.85	.68	191	2.75	3.00
Lake A	.51	.26	.87	-.53	126	3.30	2.34

b = slope
a = intercept

Those groups which demonstrated no significant differences between subsets are indicated by the vertical lines on the side.

STORMWATER RUNOFF CHARACTERISTICS AT P-10 VS P-30

Increased bacterial densities for urban stormwater runoff observed for most bacterial variables by a one-way analysis of variance. The primary interest was focused on bacterial densities between stations P-10 and P-30. Marked variations in bacterial densities existed between storms. To reduce those variations log transformed data were analyzed and the sites were paired by storm event which indicated the need for use of a two-way analysis of variance. Results indicated that this model actually fit only the SA data. No differences in SA densities were detected between stations P-10 and P-30. The F-Statistic applied for the effects of station locations for the other variables were high, so that a one-way classification was used to determine differences on an individual storm basis.

The results indicated that no differences in TC densities were observed between stations P-10 and P-30, but on the average, the following relationships existed: 1) the FC densities were 2.7X higher at P-30 than at P-10; 2) the FS densities were 5.2X higher at P-30 than at P-10; 3) the PS densities were 5.7X higher at P-30 than at P-10; and 4) the ST densities were 5.0X higher at P-30 than at P-10.

ALTERNATIVE ANALYSES

Means and 95% confidence intervals were calculated for all available low flow and storm event data derived from stations P-10 and P-30. Figures 18 and 19 include those data. Fewer monitoring dates were recorded at P-10 than at P-30. Nevertheless enough data were obtained to permit this type of visual comparison. Trends in the concentrations of bacteria can easily be recognized. At P-10 the concentrations of FC, FS, and PS all followed the general concentration trend for TC and SS but, of course, for different orders of magnitude. ST and SA curves are not included but closely resembled the curve representing FC concentrations. Only a cursory examination of the data representing P-30 (Figure 19) is required to verify earlier stated conclusions regarding the water quality at that station compared to P-10.

Bacteriological trends were not the same during storm events. For one, the values were generally higher at P-30 than P-10. And ST and SA values were considerably more erratic at P-30.

As to the causes for such concentration trends, some implication may be derived from the meteorological data

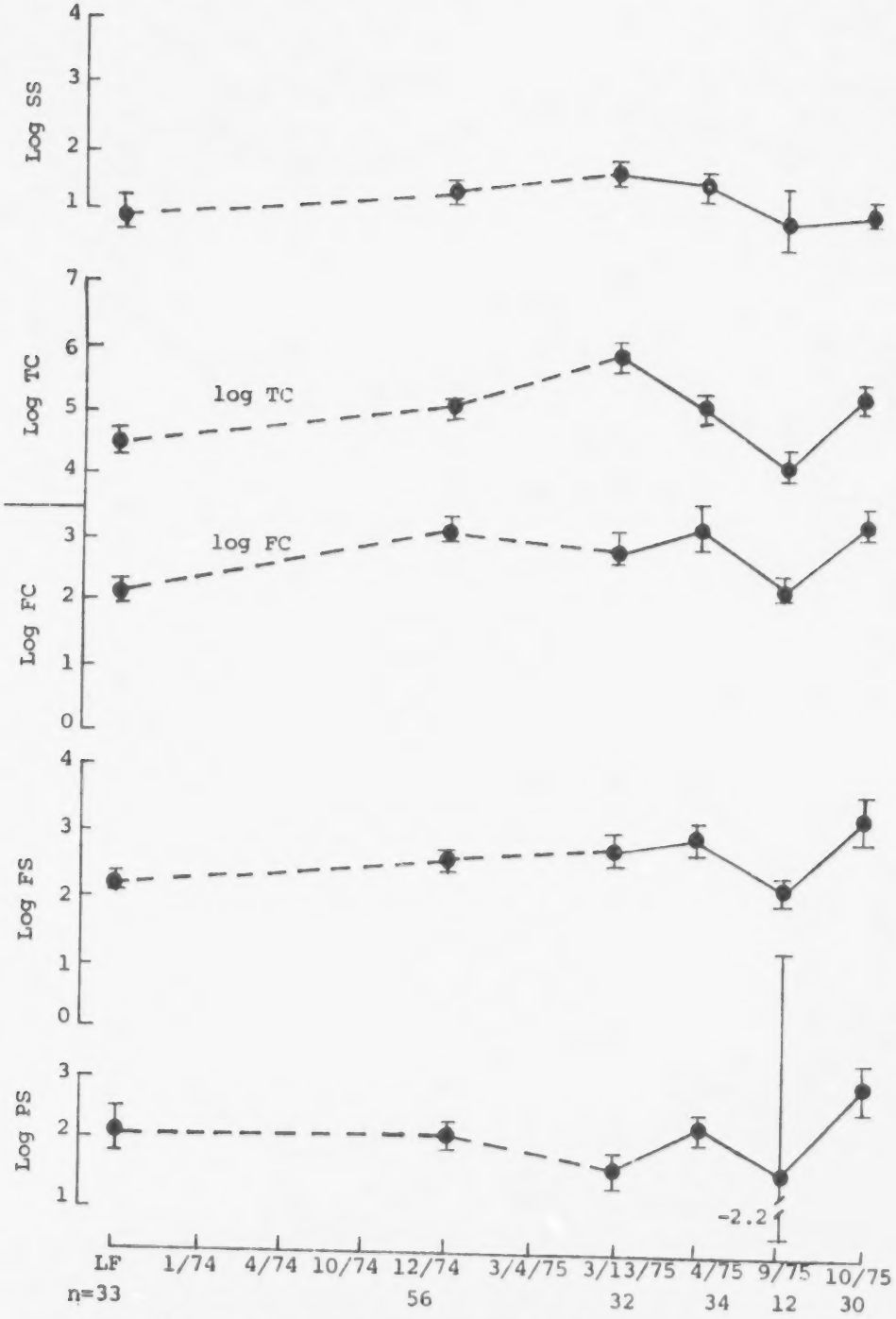


Figure 18. Indicators and pathogen relationships; low-flow and storm events. Station P-10, The Woodlands.

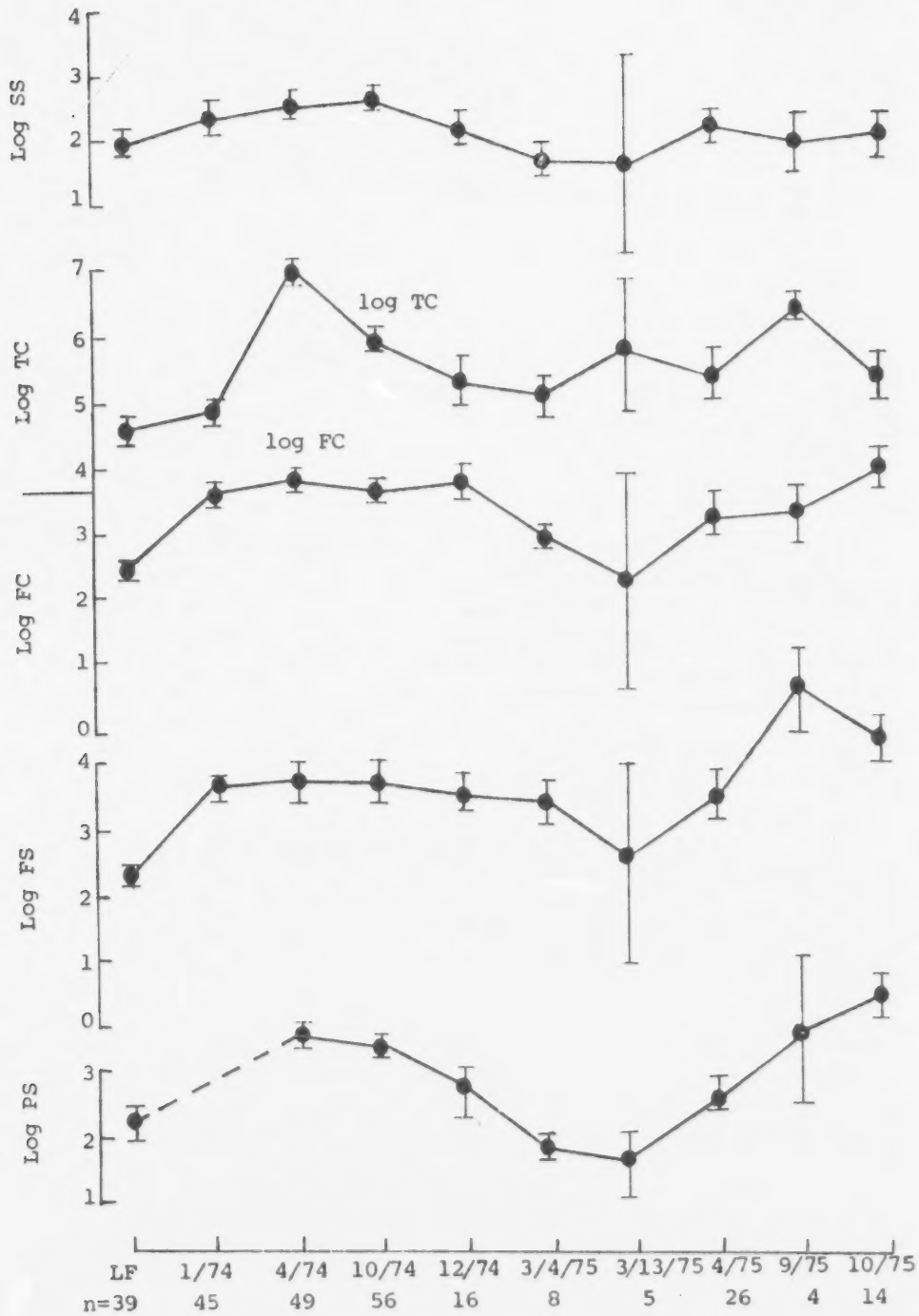


Figure 19. Indicators and pathogen relationships; low-flow and storm events. Station P-30, the Woodlands.

presented in Figure 20. A steady drying cycle can be noted in the prior monthly rainfall data. That did not follow the bacterial concentration trends. Prior week rainfall also shows no correlatable trend to bacterial densities. However, the rainfall amount and duration tended to show similarity with bacterial concentration trends at P-10. The data also refute the theory that a short term storm event of greater intensity will result in a greater leaching effect with respect to bacterial concentrations in the runoff. Note in Figure 20, with the exception of discharge (cfs), the comparatively close relationships of rainfall data between stations P-10 and P-30.

Indicator bacteria and PS mean values from 16 sites or sources were calculated and plotted in Figure 21 along with their 95% confidence intervals. The abbreviations used on the Y-axis are; raw sew. (raw sewage), Sew 2° (secondary treated sewage), Cl_2 Effl. (chlorinated secondary effluent), Sedmt. (stream sediment), LF Wood. (low flow, the Woodlands), LF LA (low flow, Lake A), LF P-10 (low flow, station P-10), LF P-30 (low flow, station P-30), LF LB (low flow, Lake B), S LA (storms, Lake A), S P-10 (storms, station P-10), S P-30 (storms, station P-30), S LB (storms, Lake B) S West. (storms, Westbury site), S Hunt. (storms, Hunting Bayou).

Those data reveal some unanticipated similarities in bacterial concentrations. For example, TC concentrations were higher in 12 sources and sites than TC values for chlorinated secondary treated municipal wastewater, excluding raw and secondary treated wastewater. Within the 95% confidence intervals many of the FC and FS levels were similar in orders of magnitude; again excluding raw and secondary treated wastewater. SA and ST trends appeared the same as that curve presented for PS. It is significant to note that the trend in the data in Figure 21 is for increased indicator and pathogen concentrations with increased urbanization. Also, the TC values indicated for Westbury site and Hunting Bayou were equal or greater than those for secondary treated wastewater.

All of the available low flow data for the Woodlands were analyzed by season of the year to determine whether temperature affected population densities. The results of those LSD and F-statistic calculations are presented in Figure 22. Statistically, no differences occurred between seasons for FC and FS. The notation at the side of the TC data indicates that the summer subset was statistically greater in itself than either the winter or spring data subset. But the winter and spring subsets were statistically equivalent. Within the pathogens, ST provided the least variation between seasons. FC/FS ratios appeared to have been higher in summer and fall than spring or winter.

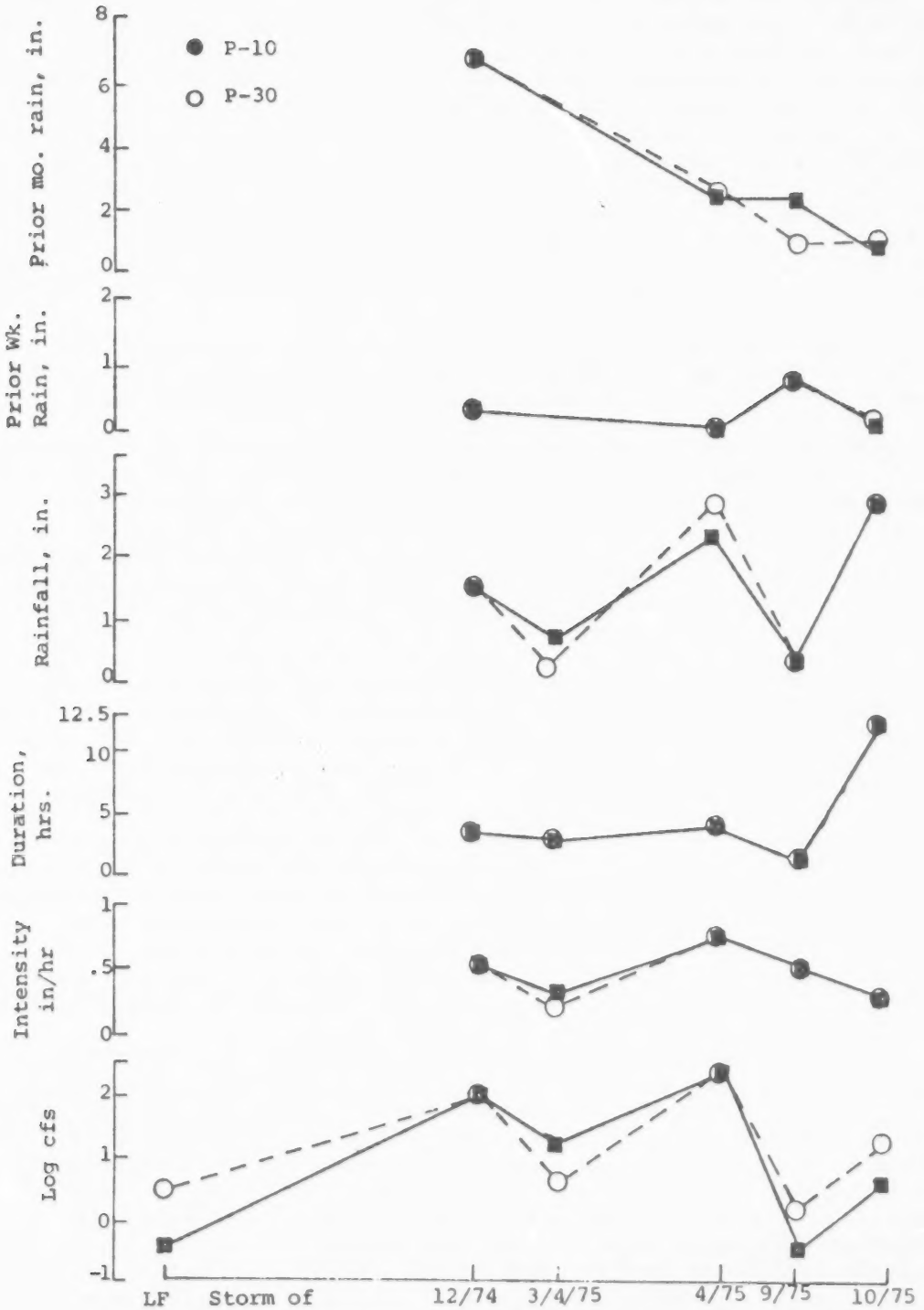


Figure 20. Low-flow vs storm rainfall occurrences at Stations P-10 and P-30.

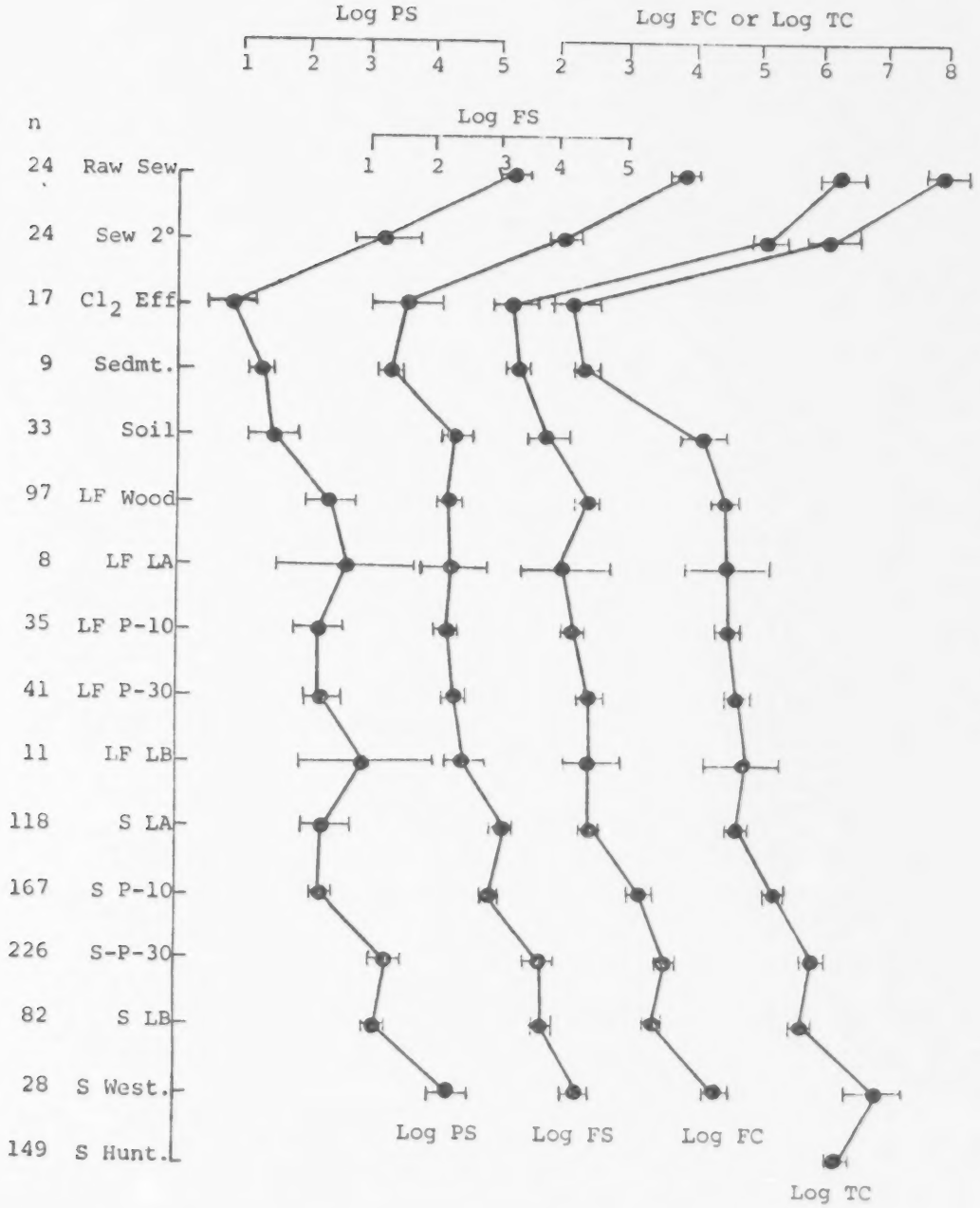


Figure 21. Comparison of low-flow, storm, sewage, soils, and stream sediment indicator and Pseudomonas densities.

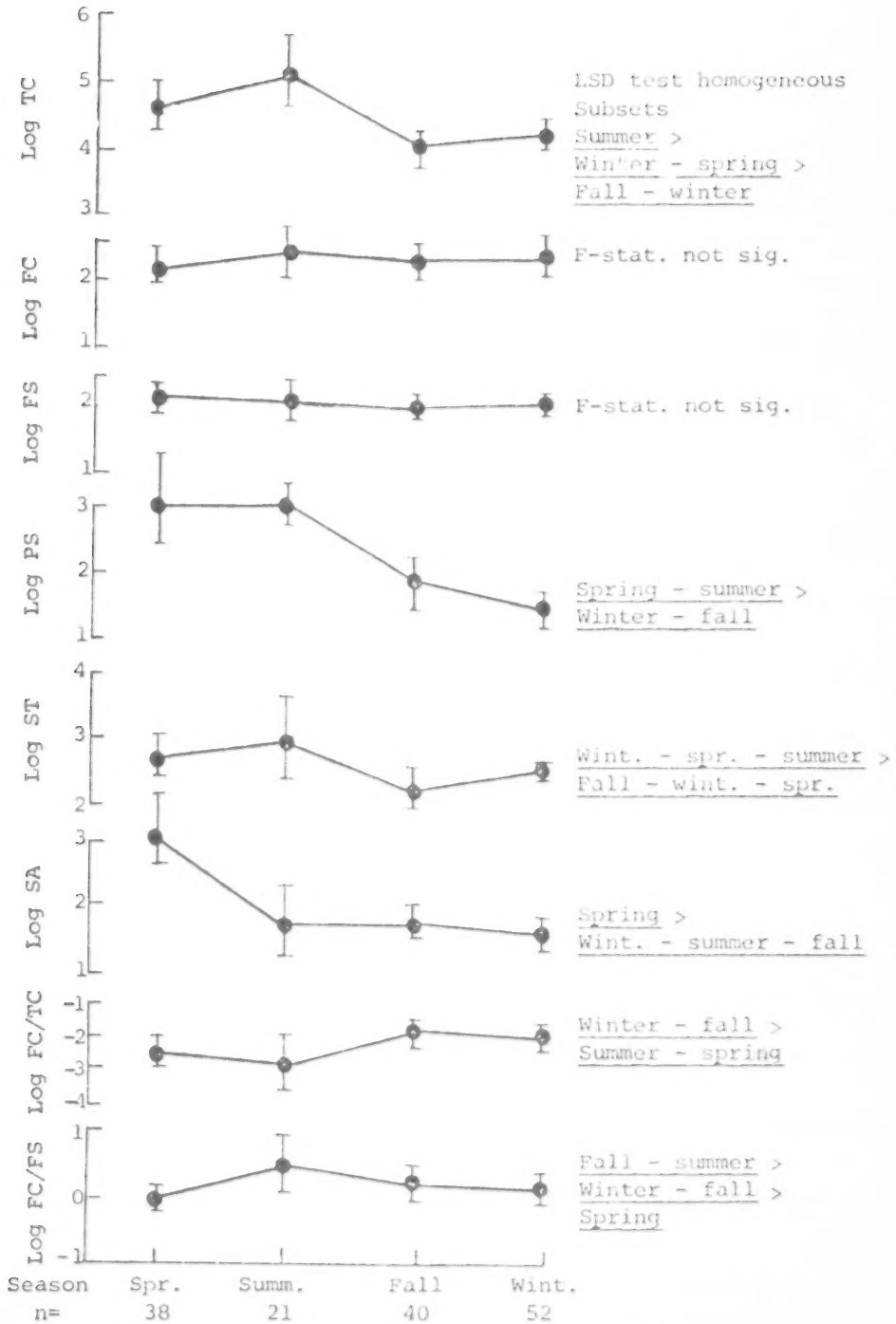


Figure 22. Woodlands seasonal low-flow variations.

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